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THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

EDITED BY

GEORGE E. HALE
Mount Wilson Observatory of the Carnegie Institution of Washington

EDWIN B. FROST
Yerkes Observatory of the University of Chicago

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Ryerson Physical Laboratory of the University of Chicago

JUNE 1920

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THE
ASTROPHYSICAL JOURNAL
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VOLUME LI JUNE 1920 NUMBER 5

ON THE APPLICATION OF INTERFERENCE METHODS TO ASTRONOMICAL MEASUREMENTS[1]

By A. A. MICHELSON[2]

ABSTRACT

An interference method of measuring extremely small angles and changes of angle.—Thirty years ago the author called attention to the possibility of measuring such minute angles as the *diameters of planetoids and satellites* and the *distance between the components of double stars* by observing the interference fringes produced at the focus of a telescope when only two portions of the objective, located on the same diameter, are used; for it was shown that as the distance apart of the apertures is increased the visibility of the fringes reaches a minimum for a distance equal to $1.22\ \lambda/\alpha$, or $0.5\ \lambda/\alpha$, for a disk or double star respectively, when λ is the effective wave-length and α is the desired angle. This beautiful and simple method was applied successfully by the author in 1891 to the accurate measurement of the size of Jupiter's satellites but was not tested on stellar objects, probably because it was supposed to require ideal seeing conditions. Last year, however, the author discovered by tests at Yerkes Observatory and at Mount Wilson that even when the "seeing" was bad, clear and relatively steady fringes could be obtained; and Anderson, using the 100-inch reflector, has recently measured the separation of the components of Capella, 0".0545, within less than 1 per cent by the application of this method. In fact the 100-inch could measure with accuracy separations as small as 0".025. But to determine the *diameter of a fixed star*, a distance between apertures of at least 10 meters would be required; so that an interferometer arrangement would have to be substituted for the telescope. The author also suggests that by the use of prisms to superpose the fringe systems of two stars, small *relative motions* and *parallaxes* could be measured.

Relative brightness of components of double stars may also be determined from the relative visibility of the focal fringes at minimum and maximum visibility.

[1] *Contributions from the Mount Wilson Observatory*, No. 184.

[2] Research Associate of the Carnegie Institution of Washington, Mount Wilson Observatory.

In the number of the *Philosophical Magazine* for July 1890 (**30**, 1) a method was described for the measurement of the angular magnitude of astronomical objects such as the diameter of planetoids and satellites and the distance between double stars, when these are beyond the powers of the largest telescopes, and the hope was there expressed that it might not be impossible thus to measure the diameter of the fixed stars.

Briefly, the process consists in utilizing only the two portions of a large objective at opposite ends of a diameter. The interference fringes at the focus under these conditions will be a series of equidistant interference bands which are most distinct with a source subtending an infinitesimal angle. For an object presenting an appreciable angle the visibility is less and may become zero—the exact relation being readily expressed for any given distribution of light in the source. Thus if $\phi(\alpha)d\alpha$ represent the intensity of a strip of the source of angular width $d\alpha$, and s the distance between the apertures (supposed small compared with s), and

if $P=\int\phi(\alpha)d\alpha$, $C=\int\phi(\alpha)d\alpha\ \cos 2\pi\frac{s}{\lambda}\alpha$, and $S=\int\phi(\alpha)d\alpha\sin 2\pi\frac{s}{\lambda}\alpha$,

then the visibility of the interference bands is

$$V=\frac{\sqrt{C^2+S^2}}{P}.$$

Thus for a double star, the brightness of whose components is in the ratio $1:r$ and whose angular distance $=\alpha$,

$$V=\frac{\sqrt{1+r^2+2r\cos 2\pi\frac{s}{\lambda}\alpha}}{1+r}.$$

For equal components this reduces to $\cos\frac{\pi s\alpha}{\lambda}$, which vanishes for $\alpha=\frac{1}{2}\frac{\lambda}{s}$. Accordingly this angle can be accurately measured when it is only half of the limit of resolution of the full-apertured telescope.

Again, by comparing the visibility at maximum and at minimum, the ratio of the brightness of the component stars may be found by

$$r=\frac{V_1-V_2}{V_1+V_2}.$$

For a uniformly illuminated disk

$$V=\int_0^1 \sqrt{1+\omega^2}\cos \omega n d\omega$$

where $n=\pi\frac{sa}{\lambda}$, a being the angular diameter. For such an object the fringes vanish for an angular diameter $a=1.22\frac{\lambda}{s}$.

A series of observations was taken on the satellites of Jupiter at the Lick Observatory the following year with results which amply confirmed the practicability and accuracy of the method.

It is clear, however, that as in all probability the stars present an angular diameter less than one-hundredth of a second, it would be almost hopeless to make such measurements, utilizing the largest telescope in existence; for it would require a distance between the apertures of at least 10 meters to observe the vanishing of the fringes.[1] While such a large telescope would be entirely out of question, the interferometer arrangements figured in the article referred to may serve the purpose, as there is theoretically no limit to the effective base line and practically only that which depends on the atmospheric disturbances.

With a view to testing the effect of these, a trial was made (August 25, 1919) with the 40-inch refractor at Yerkes Observatory, using two apertures 4 inches by 5 inches at opposite ends of a diameter. The result was very encouraging, the interference bands being remarkably steady, notwithstanding the relatively poor "seeing"—2 to 3 on a scale of 5.

On invitation from Dr. George E. Hale the test was applied (September 18, 1919) to the 60-inch reflector of the Mount Wilson Observatory and then to the 100-inch reflector, and in both cases the experience at the Yerkes Observatory was confirmed.

In the case of the 60-inch telescope the apertures were applied, as in the case of the 40-inch, to the objective; while for the 100-inch, it was found quite as effective and far more convenient to use a small screen with two apertures near the eyepiece, the distance and orientation being thus much more readily controlled while the effective size and separation of the two interfering pencils remain the same.

[1] A diminution in visibility, however, might be observed with a diameter of 2 meters.

The interference fringes in both observations remained remarkably clear and steady, notwithstanding the excessive "boiling" of the highly magnified images corresponding to "seeing" 2 on a scale of 10.

Subsequent observations showed that the interference bands remain visible even when the seeing is so poor that the usual type of observation is impracticable.

A statement of results obtained by this method by Dr. J. A. Anderson of the staff of the Mount Wilson Observatory from observations of the spectroscopic binary Capella is herewith appended.

STATEMENT OF RESULTS FROM OBSERVATIONS OF CAPELLA WITH THE MICHELSON INTERFEROMETER

Date of Observation	Distance	Position Angle	Remarks
December 30.6 1919	0".0418	(153°9)	P.A. calculated. Only the distance observed accurately*
February 13.6 1920	0.0458	5.0	
February 14.6 1920	0.0451	1.0	
February 15.6 1920	0.0443	356.4	
March 15.6 1920	0.0505	242.0	
April 23.6 1920	(0.0439)	107.0	Distance calculated. Only the position angle observed accurately†

* The rough observation of position angle was 148° ± 10°.

† Observation made in strong daylight. The blue background shifted the effective wave-length to the red, causing the observed distance of 0".0402 to be much too low. The background could not affect the position angle.

Using the following elements[1] for the orbit, these observations are satisfied as indicated:

$a_1+a_2 = 0''.05249$ $\quad (a_1+a_2) \sin i = 83{,}277{,}900$ km

$e = 0.016$

$\omega = 117°3$

$i = 140°30'$

Position angle of $\Omega = 45°55'$

$T = $ J.D. 2,422,387.9 for $P = 104.006$ days

[1] See orbit by H. M. Reese, *Astrophysical Journal*, **14**, 263, 1901, for values of $(a_1+a_2) \sin i$, of e, and of ω. a_1 and a_2 are the semi-major axes; e, the eccentricity (same for each orbit); omega is the distance of periastron from the ascending node in the plane of the orbit; i is the inclination of the orbit to the line of sight; Ω is the symbol for the ascending node and is here equivalent to the position angle on the tangential plane.

Date	$t-T$	a	i	r	Position Angle
1. December 30.6 1919	$39^d.7$	1 and 5 0".05249	180°−39°31′	0".04180	153°.9
2. February 13.6 1920	84.7	2 and 5 0.05250	−39 36	0.04583	4.6
3. February 14.6 1920	85.7	3 and 5 0.05248	−39 22	0.04506	1.0
4. February 15.6 1920	86.7	4 and 5 0.05249	−39 31	0.04430	357.3
5. March 15.6 1920	11.7	.....	−39 30	0.05050	242.4
6. April 23.6 1920	50.7			0.04391	107.2
		Means 0.05249	180°−39 30		

Parallax of Capella 0".0600.

It appears from a comparison of these results with the orbit that an order of accuracy of one ten-thousandth of a second of arc is attainable in the case of Capella with a base line of 100 inches.

In these observations the distance between the apertures was fixed, and the vanishing of the fringes was observed at the appropriate position angle.

The complete disappearance of the interference bands showed that the component stars are of equal brightness; otherwise the visibility would have a minimum from which the ratio of the brightness may be obtained as indicated above.

For this, however, it would be necessary to measure the visibility, or at least to calibrate the eye estimates.

This may be effected by adjusting the relative width of two auxiliary apertures so that the resulting visibility of a single comparison star (or of the double star in a direction perpendicular to the plane of the components) is the same as that which is actually observed.

If the ratio of the width of the apertures is ρ, then when the visibilities are equal in the two systems of fringes

$$V=\frac{2}{\rho+\frac{1}{\rho}}.$$

Other problems which involve the comparison of two stars, such as the measurement of stellar parallax, proper motion, variation of latitude, etc., may also be undertaken by a modification of the interference method. For this two prisms or prism couples are similarly placed in front of the apertures, with the plane of refraction parallel with that passing through the two apertures

and the axis. This plane is rotated until the direction coincides with that of the stars to be compared. The refraction by the prisms is then altered (by rotating the single prisms in the same plane, or by equal and opposite rotations of the elements of the prism couples) until the two systems of fringes are superposed. Any change in the relative position of the stars is accompanied by a corresponding alteration in the appearance of the fringes, which is then compensated by rotation of the prisms, from which the change in position may be determined.

Preparations are now under way at Mount Wilson for testing the possibilities of the interferometer method with a base line of 18 to 20 feet.

RYERSON PHYSICAL LABORATORY
June 1920

APPLICATION OF MICHELSON'S INTERFEROMETER METHOD TO THE MEASUREMENT OF CLOSE DOUBLE STARS[1]

By J. A. ANDERSON

ABSTRACT

Michelson interference method of measuring close double stars.—It is surprising that this method of accurately measuring angles as minute even as half the limit of resolution of the telescope used has heretofore been applied only to Jupiter's satellites. But after Michelson found by tests last year at the Yerkes Observatory and at Mount Wilson that clear and relatively steady fringes can be obtained even when the "seeing" is bad, steps were taken to apply the method to the measurement of the separation of the components of Capella. The *arrangement of apparatus* adopted is described in full. The apertures were placed near the focus instead of at the objective and set at a fixed distance apart, somewhat greater than the distance for minimum visibility, and were then rotated and the four position angles which gave minimum visibility were determined. After the *effective wave-length* for a G-type star had been found by laboratory experiments with sunlight to be about 0.550 μ, the position readings gave both the angular separation of the components and the direction of the line joining them. The *effect of atmospheric dispersion* is in general to shift the center of the system. Two methods of compensating for this effect are suggested. A method of determining the *relative brightness of components* when the ratio is not more than 1.5 is described and illustrated.

Accuracy.—In the case of Capella, the separation, about 0".05, was determined within 1 per cent. As to the *limits of applicability of the 100-inch reflector* in such measurements, the theoretical resolution limit with the interferometer is 0".025, and double stars down to about the eleventh magnitude should be measurable under ordinary observing conditions.

Elements for Capella as determined by the Michelson interference method.—Observations made on six dates, December 1919 to April 1920, give the following results: $a = 0''.05249$; T = J.D. 2422387.9; $i = 140°30'$. These combined with spectroscopic elements give: $P = 104.006$ days; $a_1 + a_2 = 130{,}924{,}000$ km; $m_1 = 4.62\odot$; $m_2 = 3.65\odot$.

Interference method of measuring atmospheric dispersion, by its effect on the fringe systems of stars at various zenith distances, is suggested by the author as likely to prove very sensitive.

The astronomical applications of the interferometer have been discussed by Professor Michelson in a number of papers.[2] He

[1] *Contributions from the Mount Wilson Observatory*, No. 185.

[2] *Philosophical Magazine* (5), **30**, 1, 1890; (5), **31**, 338, 1891; (5), **34**, 280, 1892; *American Journal of Science* (3), **39**, 115, 1890.

explains how the diameters of stars can be measured, considered as uniformly luminous disks; and, in case there is darkening toward the limb, how the amount of darkening can be determined. Further, if a celestial object is not circular in apparent shape, he explains how its exact shape may be found. Special cases, such as double stars, are fully treated.

In view of the great beauty and simplicity of the method, it is rather surprising to find that the only application it has had up to the present time is to the determination of the diameters of Jupiter's satellites, and this was done by Professor Michelson himself. It is possible that astronomers who in general are so much troubled by the phenomena of "bad seeing" have had a feeling that an instrument so extraordinarily sensitive as the interferometer is known to be could hardly, if ever, be used, especially with the larger telescopes.

On September 18, 1919, Professor Michelson made a final test of this point by applying the interferometer to the 60-inch and 100-inch telescopes of the Mount Wilson Observatory, and found that the interference fringes were easily observed, although the seeing at the time was rated about 2 on a scale of 10. He had on August 25 found similar results with the 40-inch refractor of the Yerkes Observatory. Accordingly, it was decided to give the method a trial with the 100-inch reflector, and Mr. Hale requested the writer to undertake the experiments described below.

As it appeared probable that an aperture much larger than 100 inches would be required for effective work in measuring stellar diameters, it was decided to apply the method to the measurement of some double star, if possible, to one too close to be measured with the usual method. Capella was selected, because an estimate of the separation of its components, based on knowledge of its spectroscopic orbit and parallax, places this around $\frac{1}{20}$ second of arc, which should be easy to measure with the interferometer applied to the 100-inch telescope.

A preliminary observation (by Mr. Pease and the writer) was made on December 30, 1919, the chief object of which was to learn just how the interferometer should be constructed in order that it might be suited to the measurement of double stars. This obser-

vation gave the distance between the components of Capella with a probable error of about 1 per cent; a reading of the position angle was also made, but it was so very rough that it might easily be in error by 10° either way. Regular observations with the improved form of apparatus were made on February 13, 14, and 15, March 15, and April 23, 1920.

As shown in the diagram (Fig. 1) the interferometer consists simply of a plate (*A*) having two apertures in it, placed in the

FIG. 1

converging beam of light coming from the telescope objective or mirror. The interference fringes formed in the focal plane are viewed with a high-power eyepiece *E*. The entire interferometer can be rotated about the telescope axis so as to vary the position of the line joining the centers of the two apertures; and the apertures themselves are so arranged that their distance apart can be varied, the actual separation being read on a scale at the eye end of the instrument, where the circle is also located from which the position angle of the apertures is read. The plate carrying the apertures can also be moved entirely out of the beam of light to facilitate the accurate centering of the star to be observed.

The method of making the measurements differs slightly from that described by Professor Michelson,[1] and will therefore be described in sufficient detail to be clear even without reference to any previous work.

Let the light from a star fall upon two apertures placed (for simplicity) in front of the telescope objective or mirror. Let the width of each aperture measured along the line joining their centers be *d;* let the distance between their centers be *D*. The

[1] *Philosophical Magazine* (5), 30, 1, 1890.

shape of the diffraction pattern seen in the focal plane of the telescope will depend upon that of the apertures; but we are here concerned only with its dimension in the direction of the line joining the two apertures, and this, in angular measure, as seen from a distance equal to the equivalent focal length of the telescope, is $\alpha = 2C\lambda/d$. The intensity, being, say, unity at the center of the pattern, falls to the first zero value at an angle $\alpha/2$ from this point. C is a factor depending on the shape of the apertures. For rectangular slits, $C = 1$; for circular apertures, $C = 1.22$ nearly. Upon the diffraction pattern will appear the interference fringes, these being at right angles to the line joining the two apertures. The angular distance between two bright fringes is λ/D. Hence the number of fringes which can be seen on the central diffraction disk depends on the ratio D/d, and is equal to $2CD/d$. If this number is greater than 10, the fringes farthest from the center will, in general, be invisible in white light, because of the overlapping of the different colors.

Now assume that this arrangement is pointed at a double star, the angular separation of its components being β. If β is larger than $2C\lambda/d$, two separate diffraction patterns will be seen, each with its own system of interference fringes. When β is less than $2C\lambda/d$ the patterns will overlap more or less; and if β is just equal to $\lambda/2D$ and the position angle of the double star is the same as that of the line joining the two apertures, the conditions are such that a bright fringe due to one component falls on a dark fringe due to the other component, or we may say that the two fringe systems are out of step by just one-half a fringe; and hence, if the two component stars are of the same intensity the visibility of the fringes near the center of the pattern will be zero. (It is, of course, clear that minima of visibility will occur for $\beta = N\lambda/2D$, where N is any odd integer.) Hence we may say that the interferometer "resolves" two stars whose angular separation is $\lambda/2D$, just as a circular telescope objective of diameter D will resolve two stars whose separation is $1.22\lambda/D$; that is, the resolving power of the interferometer is somewhat more than twice that of a telescope of the same aperture. It should also be borne in mind that useful measurements may be made with the interferometer

even when the angular separation is much less than $\lambda/2\,D$, as will be discussed more fully below.

Let D_0 denote the smallest value of D which will cause the fringes to disappear for a double star having equal components. If we choose D a little larger than D_0, so that $D_0 = D\cos\theta$, it is evident that the fringes will be visible when the position angle of the apertures is the same as that of the double star. If now the interferometer be rotated through an angle $\pm\theta$, the fringes will just disappear; and the same thing will happen when the instrument is rotated through an angle $180° \pm \theta$. For any value of D greater than D_0 there are, therefore, four values of the position angle, for each of which the fringes disappear, or have minimum visibility, according as the two components of the double star are of equal or of unequal intensity. From these four position angles and the known value D one can obviously find the value of D_0 and the position angle of the double star. There will, of course, be two possible position angles differing by 180°, but, as will be explained presently, unless the two components have exactly the same intensity and the same color, even this uncertainty may be removed.

The method just described was employed in the present work on Capella. As a rule, a complete observation included three complete rotations of the interferometer for each of three values of D, making a total of thirty-six readings of position angle. The values of D were so chosen that θ, as defined above, should lie between 30° and 50°. Under these conditions and with reasonably good seeing the probable error of a single reading should not exceed 3°. It is the author's opinion that with a little practice a good observer will be able to reduce the probable error of a single setting to about 1°. The corresponding error in the distance is about 1.8 per cent. The time required for a complete observation was about one hour, but it is reasonable to expect that when one becomes accustomed to observations of this kind no more than fifteen minutes will be required.

Given a suitable arrangement for measuring the "visibility" of the fringes, the following method of observation may be used. Choose a value of D smaller than D_0. Determine the visibility

at position angles differing from each other by, say, 15° all the way around the circle. If the object is a double star, the visibility will show two maxima and two minima in a revolution. (This will also be true if the object has the form of a luminous surface longer in one dimension than at right angles thereto. Further measures will, however, readily distinguish between this case and that of a double star.) Repeat twice, using two other values of D. The data thus obtained should be sufficient to determine both position angle and distance of the double star, with a high degree of accuracy, and without requiring a value of D as large as D_0.

Having found D_0 as explained above, we need to know only λ in order to compute β, since $\beta = \lambda/2\, D_0$. The value of λ for the sun was found from laboratory measures, using as an artificial double star two small round holes illuminated by sunlight reflected from freshly silvered mirrors. The constants of the apparatus were determined by direct measurements, and also by observations on the artificial double star illuminated by very nearly monochromatic light of known wave-length. The results from two series of observations with sunlight were 5498 A and 5500 A. It seems safe, therefore, to use for a G-type star $\lambda = 0.0000550$ cm, and this value was employed in reducing the observations of Capella.

In this connection it is important to bear in mind the rôle played by the background on which the interference pattern is observed. On April 23 an observation of Capella was made in full daylight. The observation was very easy to make, but on being reduced, using the value of λ given above, the distance between the components came out approximately 10 per cent too small. A little consideration shows that this might have been predicted, for the skylight, being relatively very rich in blue light, would reduce the visibility of the blue fringes much more than that of the yellow or red fringes, thus resulting in a considerable increase in the value of the effective wave-length.

EFFECTS OF ATMOSPHERIC DISPERSION

When observations are made at some distance from the zenith it is found that for certain position angles of the interferometer

the center of the fringe system does not fall on the center of the diffraction pattern and may even be displaced to such an extent that the fringes cannot be seen at all. This happens when the line joining the apertures is perpendicular to the horizon. The cause of the phenomenon is atmospheric dispersion, as became evident from a series of observations on a star at zenith distances between 50° and 20°. The phenomenon is well known to physicists who have used interferometers. For completeness, however, the explanation will be reproduced here.

To fix ideas, let us consider a star at zenith distance 45°. As seen on the sky it is really a short spectrum, the violet end above and the red end pointing down toward the horizon. Set the interferometer at right angles to this spectrum, that is, with the line joining the apertures parallel to the horizon. The fringe system will be seen central on the diffraction pattern, but the fringes will be closer together at the upper edge than at the lower, for the former are in violet light, the latter in red light. Hence the fringe system is fan-shaped, very much as indicated in the diagram (Fig. 2). Now, if we rotate the interferometer through an angle of 90°, the central fringe will no longer be white, but colored—a spectrum whose width is equal to the length of the little stellar spectrum seen on the sky. The order of colors in this fringe is violet above, red below. The angular width of this fringe for the case we are considering ($z=45°$) is about 0″.8, and is therefore equal to about ten times the distance between two bright fringes when $D=113$ cm. Consequently, in this part of the system the fringes overlap to such an extent that the result is perfectly uniform illumination. Let us for a moment imagine the atmospheric dispersion removed, all other conditions being the same. The diffraction pattern will then show a perfectly normal fringe system, the central fringe being white, the others being spectra whose dispersion increases linearly with the distance from the central fringe. For convenience let us number the fringes, calling the central fringe 0; then $+1$, $+2$, $+3$, etc., upward, and -1, -2, -3, etc., downward. The order of colors in the $+$ fringes is red above, violet below, this order being just the reverse for the $-$ fringes. Since the dispersion

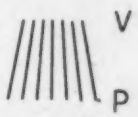


FIG. 2

increases with the order, it is evident that we can find some fringe which will have a given width, say 0".8, and hence will be an inverted duplicate of the central fringe as seen with atmospheric dispersion. This will evidently be one of the + fringes, say the $+p$th. If we now introduce atmospheric dispersion, the $+p$th fringe will be white or very approximately so, and will accordingly be regarded as the center of the system. Indeed, the fringes $p-1$, $p-2$, etc., will be violet above, red below, while the fringes $p+1$, $p+2$, etc., will be violet below, red above, as they should be. Now if p is greater than CD/d, the new central fringe will be off the diffraction pattern, in the direction away from the horizon.

We may calculate p as a function of D and the zenith distance as follows: Let the limits of the spectrum be taken as λ 4500 and λ 6500. Let the width of the +1st fringe be w, and its distance from the 0 fringe be W. The width of the pth fringe will be pw, or since $w/W = 4/11$, the width of the pth fringe is $4pW/11$. In angular measure $W = \lambda/D$ or, in seconds of arc, $W = 11".3/D$. Hence the width of the pth fringe in seconds of arc is $45".2\ p/11\ D$ where D is, of course, in centimeters.

The mean atmospheric refraction in seconds of arc for zenith distances less than about 70° is given to a sufficient approximation by $r'' = 60''$ tan z. The atmospheric dispersion between the wave-length limits chosen is 0.0138 times this, according to the values given in *Bulletin of the Bureau of Standards*, **14**, No. 4, 697–740, 1919. Hence the dispersion will be given by $\delta'' = 0".83$ tan z $= 45".2\ p/11\ D$, whence $p = 0.22\ D$ tan z. Taking $D = 150$ cm, $z = 45°$, we have $p = 33$, which indicates that with good conditions of seeing this should be a very sensitive method for the actual determination of atmospheric dispersion.

In order to make observations at all zenith distances, it is necessary to be able to compensate for this effect of atmospheric dispersion. The method thus far used is not entirely satisfactory. Two plates of plane parallel glass of exactly the same thickness are mounted, one in front of each of the apertures of the interferometer. The normals to the plane faces of these plates make an angle of about 5° with the axis of the telescope, and hence, by tilting one of the plates slightly so as to vary the angle, one of

the two beams can be retarded or accelerated with respect to the other sufficiently to bring the fringe system back to the center of the diffraction disk. Unfortunately, as the interferometer is rotated, one must constantly vary the tilt of the movable plate, and this is annoying, especially with bad seeing, when the fringes are none too easy to observe anyway. A much better way, which, however, has not been tried yet, would be to place a prism with a variable angle in front of the interferometer, but mounted so as not to rotate with the latter. By maintaining its refracting edge always downward it would then only be necessary to vary the refracting angle with the zenith distance. It should be easy to arrange the mounting so that the adjustments would be made automatically by the action of gravity.

SIZE OF APERTURES AND BRIGHTNESS

The apertures which were used with the 100-inch reflector measure 18.3×27.5 cm as seen in projection on the telescope mirror. Their distance apart was varied from about 120 to 200 cm. On the average, then, $D = 160$ cm, and $d = 0.12\,D$. With d as small as this, the diffraction disk is, of course, quite large compared to the size of the fringe system. A relatively small amount of light is admitted by the small apertures, and this is spread over a rather large area in the focal plane; hence the intensity is low. A little consideration will show that doubling the size of the apertures will result in a 16-fold increase in the intensity of the image; consequently, if we are interested in faint stars, we must use apertures as large as possible. In the present work on Capella this question was of no importance, for with such a bright star there is plenty of light for observations with small apertures even in daytime. Sufficient data were gathered, however, both with the large telescope and from laboratory experiments, to enable us to see pretty clearly just what can be done.

With $d = 0.12\,D$ it was found possible with the 100-inch reflector to observe stars down to the seventh magnitude, the seeing being usually 1 on a scale of 10. With good seeing perhaps one might reach a magnitude fainter. Laboratory experiments showed that there is practically no loss in the distinctness of the fringes when d

is as large as 0.5 D, which would increase the intensity two hundred and fifty-six times, or about six magnitudes. Hence with an instrument as large as the 100-inch, one might be able to observe stars down to the thirteenth magnitude, and there should be no difficulty in reaching the eleventh magnitude under ordinary conditions of observing. It is, of course, important to bear in mind that, as d is increased, the size of the diffraction disk decreases according to theory only if the seeing is very good. A small

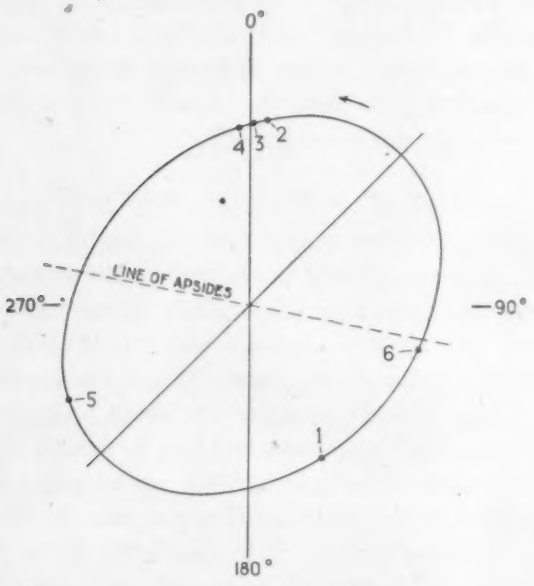


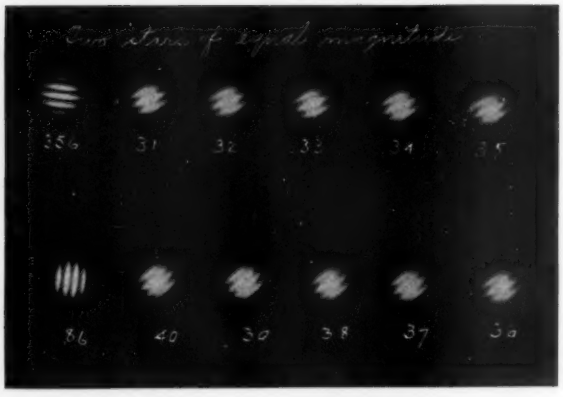
FIG. 3.—Apparent orbit of Capella

instrument will, therefore, be much more likely to reach the theoretical limiting magnitude than one as large as the 100-inch.

When d is greater than 0.3 D, so that the fringe system covers all of the diffraction disk, the normal phase-changes over the latter begin to produce an appreciable effect. If, for example, two stars of equal intensity are observed, d being greater than 0.3 D, and D being so chosen that the fringes should just disappear, one finds that although they do disappear at the center of the disk, they may still be seen at the ends of a diameter parallel to the line

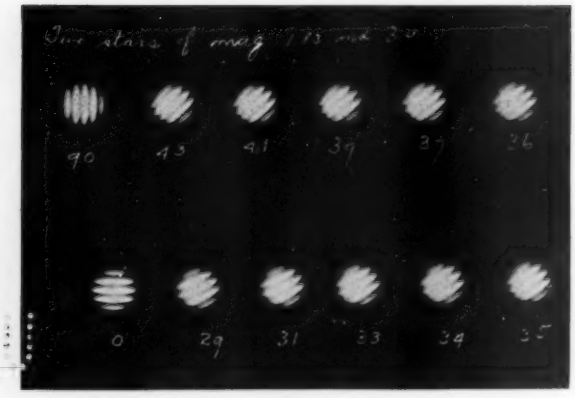
PLATE XIV

a



Position Angle of Stars 266°

b



Position Angle of Stars 270°

APPEARANCE OF INTERFERENCE SYSTEM FROM ARTIFICIAL STARS IN THE LABORATORY

joining the two stars. If, say, the star on the right side is brighter than that on the left, the fringes will be visible at the center, but will disappear at some point between the center and the left side. These phenomena are beautifully shown if D is so chosen that θ is around 45°, the fringes being inclined at 45° to the line joining the two stars. Plate XIV is reproduced from two series of photographs made to illustrate this point. The position angle of the artificial double star used in Plate XIV *a* was 266°, and the two stars had the same magnitude. The number under each image shows the position angle of the interferometer when the photograph was made. Plate XIV *b* shows a similar set for two stars in position angle 270°, their magnitudes differing by 1.17. It will be observed that in each set the image made at 35° shows the fringes on the right side out of step by half a fringe with the fringes on the left side. In *a*, however, the two systems meet in a vertical line across the center of the image, while in *b* this line is near the left edge. From this it is clear that if one uses a relatively large value of d, and the seeing is good enough to enable one to see the phenomena just described, there should be no difficulty in estimating the difference in brightness of the components, provided this does not exceed say 1.5 mag., or in removing completely the uncertainty of 180° in the value of the position angle. Experience also shows that with a pattern such as shown in Plate XIV the probable error of a single setting for θ is not greater than 1°; in fact, the probable error of the mean of 10 settings seldom exceeded 0".15. The observed co-ordinates of Capella are as follows:

RESULTS FOR CAPELLA

Observation	Date G.M.T.	Distance	Position Angle	Remarks
1.....	1919 Dec. 30.6	0".0418	148° ±10°	Position angle only roughly estimated
2.....	1920 Feb. 13.6	0.0458	5.0	
3.....	Feb. 14.6	0.0451	1.0	
4.....	Feb. 15.6	0.0443	356.4	
5.....	Mar. 15.6	0.0505	242.0	
6.....	Apr. 23.6	.....	107.0	Observed distance (0".0402) greatly in error on account of daylight

The following spectroscopic elements for Capella are taken from Campbell's *Second Catalogue of Spectroscopic Binaries:*[1]

P	T	ω	e	$a \sin i$	$m \sin^3 i$
104.022	J.D. 2414899.5	117.3	0.016	36,847,900 km	0.19
.....	.....	(297.3)	.....	46,430,000 km	0.94

Adding 72 P to T, we have $T' =$ J.D. 2422389.1 as a convenient time of periastron for our calculations. The data are not well distributed and indeed are insufficient for a complete revision of the elements; but a slight change in P is, of course, allowable, and for purposes of fitting the observed and calculated positions we may regard T' as variable with limits of ± 2 days.

Let ρ and v be the radius vector and true anomaly in the orbit plane. Let r and ϕ be the radius and angle from the node in the apparent orbit. Then

$$\rho \cos (v+\omega) = r \cos \phi$$
$$\rho \sin (v+\omega) \cos i = r \sin \phi$$

Since the eccentricity is small, we may set $\rho = a(1 - e \cos v)$ so that

$$r^2 = a^2(1 - e \cos v)^2[\cos^2(v+\omega) + \sin^2(v+\omega) \cos^2 i]$$
$$= a^2(1 - e \cos v)^2[1 - \sin^2 (v+\omega) \sin^2 i]$$

Combining the fifth observation with each of the first four we can derive four values of a. With the mean value of a we can then find five values of i. The values of a and i thus obtained should agree except for errors in the observations or in the given elements. We have assumed that the given elements are all accurate except P, as indicated above. Using $T' = 2422389.1$ we derive:

Observation	$t - T'$	M	v	a	i
1.....	$38^d.5$	133°.25	134°.59	0".05334	137° 51′
2.....	85.5	289.00	287.27	.05394	132 49
3.....	84.5	292.45	290.75	.05377	134 2
4.....	85.5	295.92	294.27	.05368	134 42
5.....	10.5	36.34	37.43	.....	134 42
6.....	49.5	171.32	171.60	.....	.....
			Mean	0.05368	

[1] *Lick Observatory Bulletin*, No. 181.

Reducing T' by 0.9 and then by 1.2 days we have:

Observation	$t-T'$	a	i	$t-T'$	a	i
1	$39^d.4$	0".05270	139°56′	$39^d.7$	0".05249	140°29′
2	84.4	.05280	138 46	84.7	.05250	140 24
3	85.4	.05276	139 11	85.7	.05248	140 38
4	86.4	.05276	139 6	86.7	.05249	140 29
5	11.4	.....	139 14	11.7	.....	140 30
	Mean	0.05275	.....	Mean	0.05249	140 30

By subtracting 1.2 days from T, we arrive at a remarkable constancy in the values of a and i, and conclude that the observations to date are best represented by

$$T' = \text{J.D. } 2422387.9, \qquad a = 0''.05249, \qquad i = 140°30'$$

Computing the distance and position angle with these values we have:

Observation	r (Observed)	Pos. Ang. (Observed)	r (Calc.)	Pos. Ang. (Calc.)	O−C	
					r	Pos. Ang.
1	0".0418	148° ±10°	0".04180	153°54′	0".00000	.....
2	.0458	5.0	.04583	4 34	−0.00003	+0°.4
3	.0451	1.0	.04506	1 0	+0.00004	0.0
4	.0443	356.4	.04430	357 18	0.00000	−0.9
5	.0505	242.0	.05050	242 26	0.00000	−0.4
6	.....	107.0	0.04391	107 12	.....	−0.2

The agreement is, perhaps, better than we have any reason to expect, due possibly to the fact that the number of observations is small. However, taking the results as they stand, we can substitute in the elements as given by Campbell and derive:

$$P = 104.006 \text{ days.} \quad a_1 + a_2 = 130{,}924{,}000 \text{ km.}$$
$$\pi = 0''.0600; \quad m_1 = 4.62\odot; \quad m_2 = 3.65\odot.$$

It remains to be seen whether recent spectroscopic observations are in agreement with this new value of the period.

MOUNT WILSON OBSERVATORY
June 1920

PHOTOGRAPHS OF NEBULAE WITH THE 60-INCH REFLECTOR, 1917–1919[1]

By FRANCIS G. PEASE

ABSTRACT

Photographs of nebulae with the 60-inch reflector.—About 330 of the nebulae found on the 66 plates taken by the author during the years 1917–1919 are listed or described in this article, and 27 of these are illustrated on the 18 plates reproduced. The most remarkable are: N.G.C. 2146, Camelopardus, with its handlike dark marking, a spiral with an abnormal center; N.G.C. 3379, resembling an unresolved star cluster; N.G.C. 3384, with a dual, Saturn-like nucleus and symmetrical wings; N.G.C. 4395–4399—4400–4401, which together form a remarkable spiral; N.G.C. 4656–4657, which constitute a single right-handed spiral without a well-defined nucleus; and I.C.II 5146 Cygnus, a unique array of light and dark markings. In addition the following are described: (1) Spirals: N.G.C. 48, 1186, 1699, 2290, 2291, 2964, 2968, 3310, 3367, 3389, 3395–3396 3786, 3788, 5257, 5258, 5278–5279, 5544, 5545, 6014 (?), 6906, 6928, 6930, 7722; I.C.II 1441, 2233. (2) Round or elongated: N.G.C. 49, 51, 1700, 2274, 2275, 2288, 2289, 2970, 3377, 3391, 5557, 5868, 5869, 6017, 6927, 7240, 7242, 7435, 7436, 7611, 7615, 7617, 7619, 7621, 7623, 7627, 7631; I.C.I 922, 928; I.C.II 5192, 5194, 5195. (3) Misc.: N.G.C. 955, 2294 (spindles); 1491, 1555, 2024, 2245, 2247, 2359, 2403, 2537, 6820, 6888, 7023 (irregular); 3357 (stellar); 6703(?), 7048 (planetary); I.C.I 931 (stellar); 1470 (irregular); I.C.II 5191 (spindle). (4) Uncatalogued nebulae numbering 255. *Variations from N.G.C.*—The positions for N.G.C. 48, 49, 51, 2247, 5544, 5545, 6927, 6928, and 6930 were given incorrectly. N.G.C. 5865, 5871, and 7433 were not found. N.G.C. 6823 is a cluster and N.G.C. 6846 is a group of stars. In four cases, indicated above by dashes, two or more nebulae seem to form parts of a single system. *Variable nebulae.*—The changes in N.G.C. 1555 are described and also possible differences in the nuclear region of N.G.C. 2245, which will be investigated further. Other nebulae, N.G.C. 955, 1186, 2024, and 7023, showed no change.

Spectra of two nebulae.—N.G.C. 1700 is of type Go or later and has a large radial velocity. The spectrum of the nucleus of N.G.C. 3379 is Go or later and the radial velocity is +850 km per sec.

This series of observations of nebulae covers the writer's work in direct photography with the 60-inch reflector during the years 1917–1919. The program included (*a*) peculiar nebulae, e.g., N.G.C. 3395–3396; (*b*) groups of nebulae with a view to future measurement, e.g., N.G.C. 48, 49, 51; I.C.I 922, etc.; (*c*) variable nebulae such as N.G.C. 1555; (*d*) previously observed nebulae requiring additional photographic data, these being indicated with

[1] *Contributions from the Mount Wilson Observatory*, No. 186.

an asterisk thus: N.G.C 955*; (*e*) a few objects for special purposes, and several affording data for classification photographed during intervals in the regular program. In addition a search for spirals was made along the Milky Way among the smaller nebulae with no success thus far.

Trails for orientation were made on practically all the plates. Many of the measures have been made with a polar co-ordinate machine; and while this serves admirably for the determination of orientation and distances, the magnification (12) is too high for use in determining the size of the objects. For these data recourse was had to the polar co-ordinate réseau and a low-power magnifier. Many objects appearing near the edges of the plates have been listed; but it is to be remembered that at 10′ from the center of the field a star image is oval, and at 15′ it is comate or arrow-shaped, although poor seeing rounds out these forms, with some increase in size. The smaller nebulae not listed in the N.G.C., or the *Index Catalogue*, are listed as *a*, *b*, *c*, etc., in order of their right ascension.

The descriptions apply to a particular plate or to the general results from a number of plates of the same object, and are not co-ordinated into a homogeneous series of intensities corresponding to the N.G.C. The nebulae have been separated into four orders of brightness: faint, F; medium faint, MF; medium bright, MB; bright, B. The following abbreviations have also been used in the descriptions: R, round; Irr., irregularly; gbM, gradually brighter in the middle; lbM, little brighter in the middle; Nu., nucleus; sbM, suddenly brighter in the middle. All illustrations are placed with N at the top, *p* on the right.

As before, the positions are those of the N.G.C. brought forward to the year 1920. A number of these have been found incorrect, and recourse has been had to Bigourdan's *Observations des Nebuleuses et d'Amas Stellaires* to obtain the correct data.

Photographs of several objects taken with the 100-inch reflector have been used in this paper and are designated with the prefix 100—. Several of Mr. Shapley's photographs showing nebulae have been used in compiling the descriptions. These are designated as *Shapley* 2968, etc.

TABLE I

NEGATIVES WITH THE 60-INCH REFLECTOR

N.G.C.	α 1920	δ 1920	Constellation	G.C.	H and Others	h	Type	Plate No.	Illustration	Remarks
48.....	$0^h\ 9^m52^s$	+47°47′.8	Lacerta	.....	Barnard	.....	Spl.	309		8 additional
49.....	0 10 13	48.0	Lacerta	.....	A.N.	.....	Elong.	309		Nebulae on plate
50.....	0 10 26	48.9	Lacerta	.....	4136	.....	Elong.	309		
955*.....	2 26 29	− 1 27.8	Cetus	551	II 278	229	Spe.	319		15 additional
1186*.....	3 0 16	+42 30.9	Perseus	639	IV 43	281	Spl.	310	XV*d*	20 additional
1491.....	3 57 21	+51 5.6	Perseus	791	I 258	.....	Irr.	308	XV*c*	
1555*.....	4 17 17	+19 20.1	Taurus	839	Hind	.....	Var.	312, 322		
1699.....	4 53 3	− 4 52.8	Eridanus	.....	.....	.....	Spl.	314, Hoge 3		
1700.....	4 53 0	− 4 50.3	Eridanus	932	IV 32	336	R	314, Hoge 3		
2024.....	5 37 49	− 1 53.0	Orion	1227	V 28	.....	Irr.	316		
2146.....	6 5 53	+78 23.	Camelopardus	5357	Winnecke	TI	Spl.	358	XV*f*	
2245.....	6 28 17	+10 13.2	Monoceros	1425	IV 3	393	Fan.	323, 329	XVI*a*	
2247.....	6 28 45	+10 23.7	Monoceros	.....	Ld. R, Swl	.....	Irr.	323, 329		
2274.....	6 42 2	+33 39.0	Gemini	1448	II 615	406	R	313		
2275.....	6 42 3	41.0	Gemini	1449	II 614	407	R	313		
2288.....	6 45 28	29.1	Gemini	1455	Ld. R	.....	R	311, 315		
2289.....	6 45 29	30.9	Gemini	1456–7	II 898	410	Elong.	311, 315		12 additional
2290.....	6 45 33	27.7	Gemini	5369	III 897?	.....	Spl.	311, 315	XVI*a*	
2291.....	6 45 35	33.0	Gemini	1458	III 897?	409	Spl.	311, 315		
2294.....	6 45 47	33.2	Gemini	1460	Ld. R	.....	Spe.	311, 315		
2359.....	7 13 50	−13 4.1	Canis Major	1511	V 21	3075	.....	320	XVI*b*	
2403*.....	7 29 7	+65 46.5	Camelopardus	1541	V 44	.....	.....	307		
2537.....	8 7 35	+40 14	Lynx	.....	.....	.....	Irr.	359, Sh.2968		
2903.....	9 27 39	+21 51.2	Leo Major	1861	I 56	6041	Single	282		No text given
2905.....	9 27 41	+21 52.3	Leo Major	1863	I 57	6042	Spl.			
2964.....	9 38 11	+32 12.8	Leo Minor	1896	I 114	622	Spl.	321, 324		15 additional
2968.....	9 38 28	+32 17.7	Leo Minor	1899	II 491	624	El. Spl.	321, 324		
2970.....	9 38 48	+32 20.7	Leo Minor	1901	.....	627	Elong.	321, 324		
3310.....	10 33 48	+53 55.1	Ursa Major	2158	IV 60	731	Spl.	356		
3357.....	10 40 6	+14 30.3	Leo Major	5533	.....	.....	Neb. Star	291		No text given
3367.....	10 42 21	+14 10.2	Leo Major	2193	II 78	748	Spl.	289, 327	XV*e*	9 additional
3377.....	10 43 28	+13 24.4	Leo Major	2201	II 99	754	Elong.	289, 327		4 additional
3379.....	10 43 37	+13 0.2	Leo Major	2203	I 17	757	R	290, 334		
3384.....	10 44 4	+12 3.1	Leo Major	2207	I 18	758	Elong.	290, 334		
3380.....	10 44 14	+12 57.0	Leo Major	2211	II 41	761	Spl.	290, 334	XVII*a*	
3391.....	10 44 45	+14 38.6	Leo Major	5535	.....	.....	Elong.	289, 327		See text 3377
3395.....	10 45 23	+33 24.4	Leo Minor	2216	I 116	765	Double	286, 332	XVIII*a*	
3396.....	10 45 28	+33 24.9	Leo Minor	2217	I 117	760	Spiral			
3786.....	11 35 29	+32 21.3	Ursa Major	2479	.....	931	Spiral	337, 338	XV*b*	26 additional
3788.....	11 35 32	+32 22.8	Ursa Major	2480	.....	932	Spiral			
4395.....	12 21 51	+33 59.4	Canes Venatici	2958	V 29.1	1252	Single			
4399.....	12 22 ≐	+34 ≐	Canes Venatici	2959	V 29.2	.....	.....			
4400.....	12 22 ≐	+34 ≐	Canes Venatici	2960	Ld. R	.....	Spiral	330, 331, 333	XVII*b*	
4401.....	12 22 1	+33 57.5	Canes Venatici	2962	Ld. R	.....	.....			

4656	12 40 5	+32 36.2	Canes Venatici	3189	I 176	1414	Single	336, 339	XVIIIb	11 additional
4657	12 40 14	+32 39.4	Canes Venatici	3190	I 177	1415	Spl.			
5257	13 35 49	+ 1 14.7	Virgo	3624	II 895	1654	Spl.	345	XIXb	
5258	13 35 53	+ 1 14.3	Virgo	3625	II 896	1655	Spl.	345		
5278	13 38 40	+56 4.3	Ursa Major	3639	II 798	1665	Single	341, 342	XIXa	
5279	13 38 45	+56 4.5	Ursa Major	.....	Ld. R	1665a	Spl.			
5544*	14 13 40	+36 56.5	Boötes	3833	II 419	1771	Spl.	127, 260, 261	XXb	13 additional
5545*	14 13 41	+36 56.8	Boötes	3834	Ld. R	.....	Spl.	127, 260, 261		
5557	14 15 5	+36 51.6	Boötes	3843	I 99	1776	Elong.	127, 260, 261		
5865	15 5 43	+ 0 48.	Serpens	4057	II 684	.....	.....	328, 335		Not on plate
5868	15 5 44	+ 0 50.2	Serpens	4060	dA	.....	R	328, 335		
5869	15 5 45	+ 0 46.6	Serpens	4061	II 545	1908	Elong.	328, 335		
5871	15 5 57	+ 0 49.1	Serpens	.....	.....	T V	.....	328, 335		Not on plate
6014	15 52 1	+ 6 9.7	Serpens	4148	.....	1940	Spl?	325		
6017	15 53 19	+ 6 13.6	Serpens	4150	.....	1941	Elong.	325		
6703*	18 45 0	+45 27.7	Lyra	5931	.....	.....	Plan?	344		10 additional
6820	19 39 3	+22 53.3	Vulpecula	5945	.....	.....	Irr.	298		
6823	19 39 48	+23 6.5	Vulpecula	4512	VII 18	2049	Cluster	298		
6846	19 53 22	+32 8.4	Cygnus	5948	.....	.....	Group of stars	295		
6888	20 9 33	+38 9.1	Cygnus	4561	IV 72	.....	Irr.	299, 301, 348	XXc	
6906	20 19 36	+ 6 12.3	Sagitta	5956	m 40	.....	Sp.	352		
6927	20 28 46	+ 9 38.6	Delphinius	5962	.....	.....	Elong.	347, 350		4 additional
6928	20 28 58	+ 9 39.2	Delphinius	5963	.....	.....	Spl.	347, 350		
6930	20 29 7	+ 9 34.6	Delphinius	5964	.....	.....	Spl.	347, 350		
7023*	21 0 37	+67 51.	Dr ...	4634	IV 74	.....	Irr.	343		
7048	21 11 23	+45 57.4	Cygnus	.....	St. IV	.....	Plan.	296		
7240	22 11 53	+36 52.7	Lacerta	6033	St. V	.....	Elong.	292, 354, 357		19 additional
7242	22 12 10	+36 53.7	Lacerta	6035	St. V	.....	Elong.	292, 354, 357		
7431	22 53 47	+25 44.2	Pegasus	.....	Bigourdan	.....	.....	293		Star on plate
7433	22 54 2	+25 43.2	Pegasus	4872	Ld. R	.....	.....	293		Not on plate
7435	22 54 6	+25 42.2	Pegasus	4873	Ld. R	.....	R	293		
7436	22 54 6	+25 43.3	Pegasus	4871	III 243	2195	R	293		14 additional
7611	23 15 33	+ 7 22.5	Pegasus	4934	dA	.....	Elong.	351		
7615	23 15 53	+ 7 58.5	Pegasus	4935	.....	2229	Elong.	351		
7617	23 16 2	+ 7 43.7	Pegasus	6186	m 572	.....	Elong.	351		
7619	23 16 12	+ 7 46.	Pegasus	4936	II 439	2230	R	351		
7621	23 16 20	+ 7 55.7	Pegasus	6188	m 574	.....	Elong.	351		
7623	23 16 27	+ 7 57.5	Pegasus	4938	III 435	2231	R	351		
7626	23 16 39	+ 7 46.7	Pegasus	4940	II 440	2233	R	351		
7631	23 17 24	+ 7 46.7	Pegasus	4942–3	Ld. R	.....	Elong.	351		
7722	23 34 41	+15 31.0	Pegasus	6216	.....	.....	Spl.	353		
I 922	13 40 17	+56 0.4	Ursa Major	Barnard AN 4136	.....	.....	.....	341, 342		72 additional
I 928	13 40 43	+56 1.2								
I 931	13 40 49	+56 1.3								
I 1441	22 11 47	+36 53.8	Lacerta	.....	Bigourdan	.....	.....	292		See text N.G.C. 7240
I 1470	23 1 51	+59 48.9	Cassiopeia	Spitalier 62	Barnard 3110	.....	Irr.	297	XXa	3 additional
II 2233	8 8 19	+45 59.5	Lynx	.....	.....	.....	Spl.	Sh.2968, 359		
II 5146	21 50 25	+46 53.2	Cygnus	Espin	Wolf	.....	Irr.	276, 349	XIXc	
II 5191	22 12 7	+36 52.8	Lacerta	.....	.....	.....	.....	292		See text N.G.C. 7240
II 5192										
II 5194										
II 5195	22 12 11	+36 53.8		.....	.....	.....	.....	.....		

To increase their sensitiveness, the plates were given a preliminary exposure. Before use at the telescope they were exposed to an 8 c. p. red lamp at a distance of six feet. The amount varied from twenty to forty seconds, depending upon the length of exposure to be given at the telescope.

Mr. W. P. Hoge, Mr. J. C. Duncan, Mr. Hugo Benioff, and Mr. Milton Humason have assisted in making the plates, and to them the writer wishes to express his gratitude for the help rendered. I am indebted to Mr. Ellerman for the preparation of the positives for the half-tones.

N.G.C. 48, 49, and 51, Lacerta

N.G.C. 48 $\alpha = 0^h\ 9^m52^s$, $\delta = +47°47'.8$
N.G.C. 49 $\alpha = 0\ 10\ 13$, $\delta = +47\ 48.0$
N.G.C. 51 $\alpha = 0\ 10\ 26$, $\delta = +47\ 48.9$
(1920); $\lambda = 84°$, $\beta = -14°$

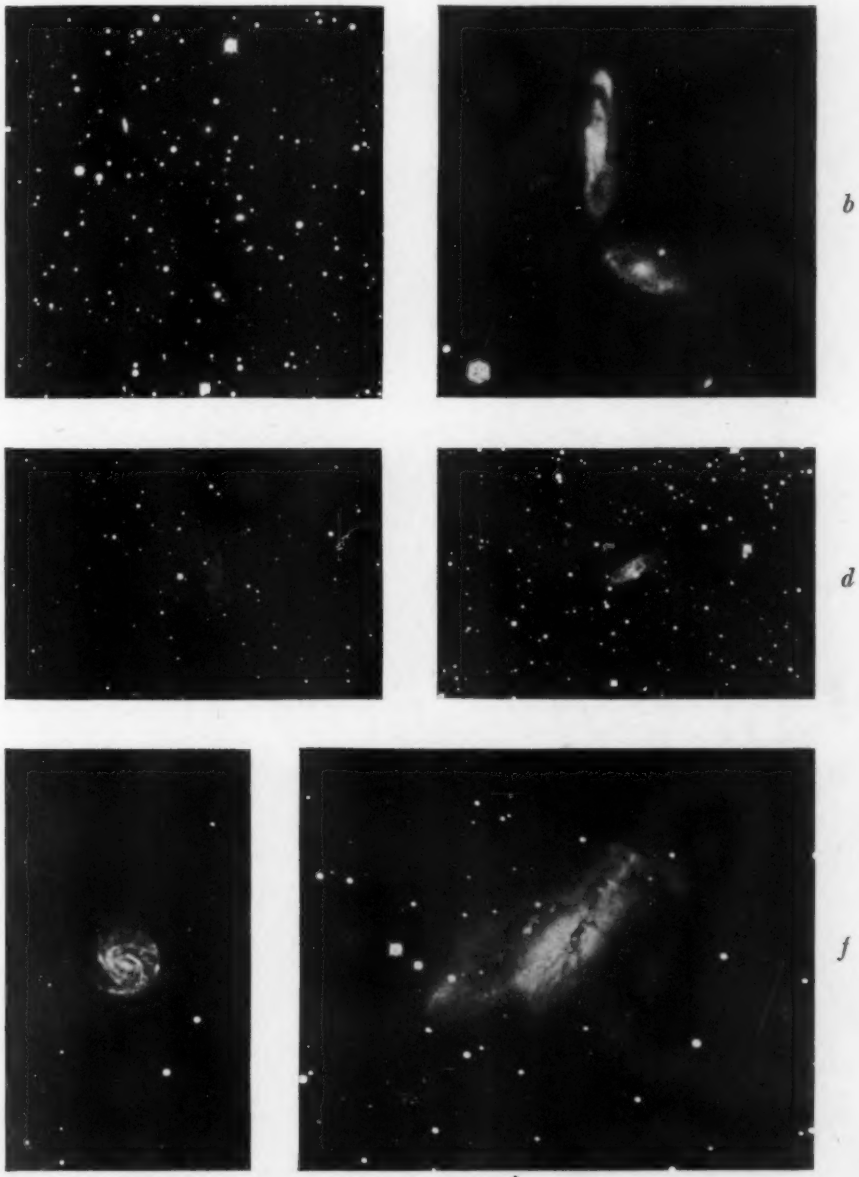
Plate No. 309, 1917, November 16, 130^m. Images large

A group of eleven nebulae, six of which are described by Barnard in *A.N.* 4136. Eight are elliptical in shape, the other three irregularly round. Two have distinct spiral structure, four have strong bright almost stellar nuclei. Two are medium-faint, almost uniform spindles, and the remainder, faint patches with slightly brighter middle.

The positions given in the N.G.C. are not correct, those above being obtained from Barnard's corrected values. The following is a description of the nebulae, measures being referred to the nucleus of N.G.C. 51.

a,	*p* 250°	*d* 15'.5	MF		12″×6″, *p* 161°.
b,	234	10.5	MB		20″×10″, *p* 65°, almost stellar Nu.; Barnard No. 1.
c,	227	8.7	MB		Spiral, 45″×15″, *p* 168°, gbM, vs almost stellar Nu.; Barnard No. 2.
d,	257	5.7	MB		Spiral, 45″×30″, *p* 11°, N.G.C. 48, Barnard No. 3.
e,	202	7.3	MF		9″ diameter with almost stellar Nu., Barnard No. 4.
f,	308	2.7	F		10″ diameter gbM.
g,	256	2.1	MF		12″×9″, *p* 161°, gbM, B almost stellar Nu., N.G.C. 49, Barnard No. 5.
h,		0	MB		30″×18″, *p* 59°, B, almost stellar Nu. on sp edge of central B patch 10″ diameter, N.G.C. 51, Barnard No. 6.

PLATE XV

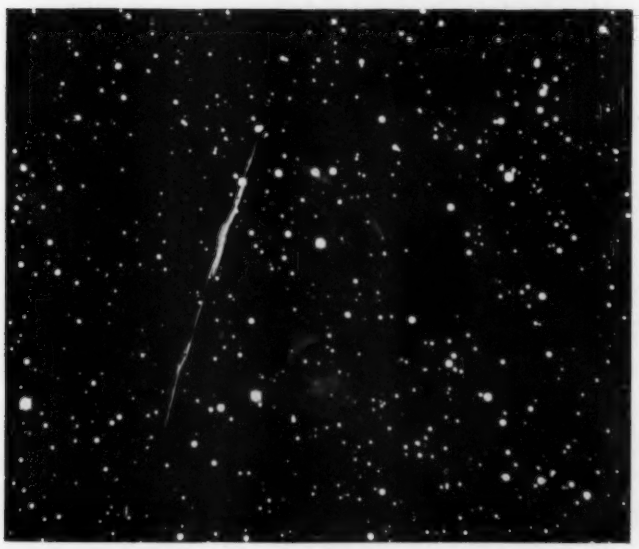


a. N.G.C. 2288,2289,2290,2291,2294, Exposure, 210^{m} S 27, Enlargement, 1.9, 1 mm = 14.″4
b. N.G.C. 3786, 3788 Exposure, 135 S 27, Enlargement, 5.6, 1 mm = 4.9
c. N.G.C. 1491 Exposure, 160 S 23, Enlargement, 1.9, 1 mm = 14.4
d. N.G.C. 1186 Exposure, 220 S 27, Enlargement, 1.9, 1 mm = 14.4
e. N.G.C. 3367 Exposure, 150 S 30, Enlargement, 2.4, 1 mm = 11.2
f. N.G.C. 2146 Exposure, 258 S 23, Enlargement, 3.5, 1 mm = 7.8

PLATE XVI

a

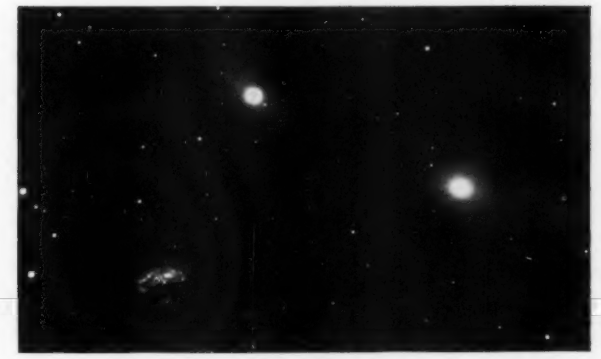
b



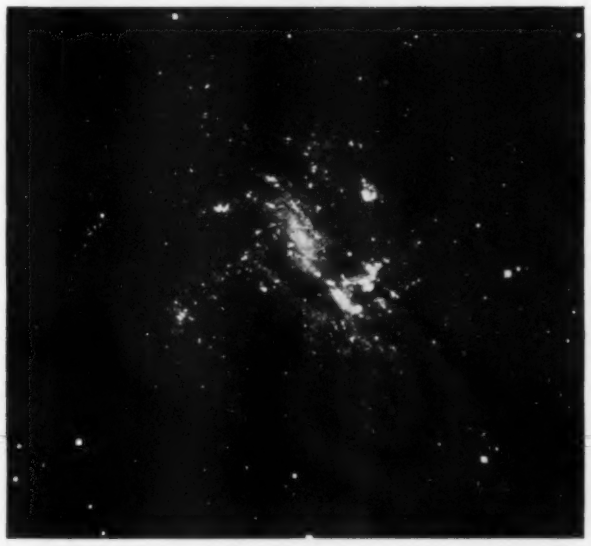
a. N.G.C. 2245, 2247, Exposure, 95^{m} S 30, Enlargement, 1.9, 1 mm = 14.″4
b. N.G.C. 2359, Exposure, 210 S 23, Enlargement, 2.5, 1 mm = 11.0

PLATE XVII

a



b



a. N.G.C. 3379, 3384, 3389, Exposure, 120^{m} S 23, Enlargement, 1.9, 1 mm = 14″.4
b. N.G.C. 4395, 4399, 4400, 4401, Exposure, 450 S 30, Enlargement, 2.0, 1 mm = 13.3

PLATE XVIII

a

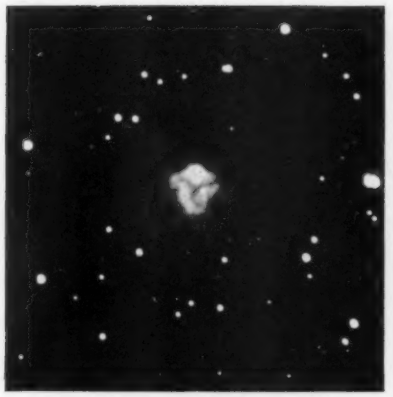
b

a. N.G.C. 3395–96, Exposure, 120^{m} S 23, Enlargement, 5.6, 1 mm = 4.″9
b. N.G.C. 4656–57, Exposure, 240 S 30, Enlargement, 1.9, 1 mm = 8.5 (100-inch)

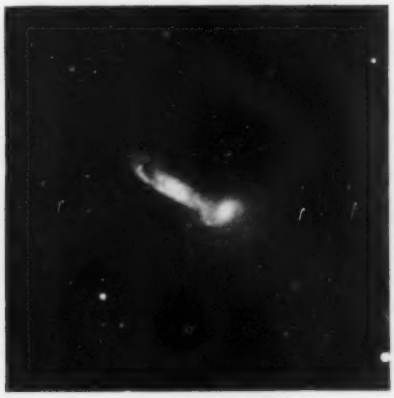
PLATE XIX

a. N.G.C. 5278–79, Exposure, 160^{m} S 30, Enlargement, 3.5, 1 mm = 7.8
b. N.G.C. 5257, 5258, Exposure, 50 S 30, Enlargement, 3.5, 1 mm = 7.8
c. I.C. II 5146, Exposure, 300 S 23, Enlargement, 1.9, 1 mm = 14.4

PLATE XX



a



b

c

a. I.C. I 1470, Exposure, 190^{m} S 23, Enlargement, 5.5, 1 mm = 5.″0
b. N.G.C. 5544, 5545, Exposure, 360 S 27, Enlargement, 5.5, 1 mm = 5.0
c. N.G.C. 6888, Exposure, 300 S 30, Enlargement, 2.4, 1 mm = 11.2

i,	0	8.0	F	Patch 10″ diameter.
j,	13	6.4	MF	Patch 10″ gbM.
k,	18	10.7	MF	Spindle 30″×6″, *p* 19°, gbM.

N.G.C. 955,* Cetus

$\alpha = 2^h26^m29^s$, $\delta = -1°27'.8$ (1920); $\lambda = 138°$, $\beta = -54°$

Plate No. 319, 1917, December 17, 30^m; 18, 65^m. Total 95^m. Images large

A so-called variable nebula, but thought by Dreyer to be unchanging. This plate was made for comparison with No. 229. It is stronger than the 1913 plate; the general dimensions are increased to 113″×10″, but there is no change of relative intensity in the different parts of the nebula. Many small nebulae are shown on both plates; 15 of the more important ones are as follows, the measures referring to the nucleus of N.G.C. 955:

a, *p*	249°, *d*	16′.3	Nebulous spot.
b,	346	15.1	F, uniform, 8″ diameter.
c,	214	4.9	F, spindle, 20″×4″, *p* 32°, BM.
d,	31	8.2	F, sliver, 10″×2″, *p* 15°.
e,	35	6.9	MF, spindle, 12″×3″, *p* 115°, gbM.
f,	162	13.6	MF, spindle, 20″×6″, *p* 44″, gbM, Nu.
g,	156	16.0	MF, spindle, 5″ diameter, gbM, Nu.
h,	59	7.9	F, sliver, uniform, 15″×3″, *p* 30°.
i,	88	8.5	MF, uniform 12″ diameter, with Nu. 2″ diameter elongated 143°.
j,	146	14.3	F, uniform, 6″ diameter.
k,	146	20.0	MF, 8″ diameter, gbM.
l,	84	16.5	MF, spindle, 10″×4″, *p* 63°, gbM, Nu.
m,	61	20.5	MB, spindle, 13″×6″, *p* 40°, gbM, Nu. (edge of plate).
n,	94	17.8	F, 8″ diameter gbM (edge of plate).
o,	98	19.2	MF, 10″ diameter gbM (edge of plate).

N.G.C. 1186,* Perseus

$\alpha = 3^h0^m16^s$, $\delta = +42°30'.9$ (1920); $\lambda = 115°$, $\beta = -13°$

Plate No. 310, 1917, November 16, 220^m. S 27.
Images large. Illustrated Plate XV*d*

This photograph was made for comparison with No. 245, taken in 1914. This supposedly variable nebula has undergone no relative change since 1914. The longer exposure brings out, however, the spiral structure more clearly and shows the nebulosity extending to 2′.5×0′.8. The arrangement of the arm is not regular.

Many small nebulae are on the plate, among them the following. The measures refer to the nucleus of N.G.C. 1186, and not to the star.

a,	*p* 233°,	*d* 18.8	MF,	9″ diameter, nebulous spot, fades at edges.
b,	326	19.9	MF,	8″ diameter, nebulous spot, fades at edges.
c,	229	13.7	MF,	10″ diameter, nebulous spot, gbM.
d,	229	12.2	MF,	6″ diameter, nebulous spot, gbM.
e,	312	11.1	F,	7″×2″, *p* 135°, nebulous patch.
f,	262	8.0	MF,	7″×2″, *p* 50°, nebulous spot.
g,	331	15.8	MF,	5″ diameter, nebulous spot, gbM.
h,	346	12.5	F,	4″ diameter, nebulous spot, gbM.
i,	349	13.3	F,	4″ diameter, nebulous spot, gbM.
j,	190	10.6	MF,	5″ diameter, nebulous spot, gbM.
k,	350	7.3	F,	5″ diameter, nebulous spot, gbM.
l,	353	11.2	MF,	11″ diameter, nebulous spot, gbM.
m,	357	9.5	MF,	3″ diameter, nebulous spot, gbM.
n,	178	5.3	MB,	35″×6″, *p* 65°, spindle, stellar Nu.
o,	87	1.8	F,	10″×2″, *p* 23°, thread.
p,	55	2.5	MF,	10″×8″, *p* 9°, nebulous spot, gbM.
q,	141	7.6	MB,	8″ diameter, almost a nebulous star.
r,	73	7.0	F,	5″ diameter, nebulous spot, gbM.
s,	90	13.6	B,	9″ diameter, nebulous star.
t,	55	17.4	MB,	7″ diameter, nebulous spot.

N.G.C. 1491, Perseus

$\alpha = 3^h57^m21^s$, $\delta = +51°5'.6$ (1920); $\lambda = 118°$, $\beta = -1°$

Plate No. 308, 1917, October 20, 45^m. Cramer Crown. Images small and round

Plate No. 355, 1919, December 22, 160^m. S 23. Images small and round. Illustrated Plate XV*c*

A tuft of wispy nebulosity, roughly triangular in shape, about 3′ on a side. The effect is produced by three principal V-shaped streamers or filaments, included angle 80°–90°, pointing *p* 225°. They are displaced with respect to one another and thus cross. A star of magnitude 10–11 lies in the fainter nebulosity filling the V.

N.G.C. 1555, Taurus

$\alpha = 4^h17^m17^s$, $\delta = +19°20'.1$ (1920); $\lambda = 144°$, $\beta = -20°$

Plate No. 312, 1917, November 17, 195^m. S 27. Images small and elongated

Plate No. 322, 1918, February 11, 110^m; 12, 100^m; 13, 110^m. Total 320^m. S 27. Images medium and round

Plate No. 326, 1919, March 1, 90^m. S 30. Images small and round

For previous descriptions and chart see *Mount Wilson Contribution*, No. 127; *Astrophysical Journal*, **45**, 89, 1917. All three plates show nebulosity *A* remaining about the same, nebulosity *C* extending farther to the W and N. Traces of *G* show as before, while dark regions not sketched show S and E of *K* and *H*.

N.G.C. 1699, 1700, Eridanus

N.G.C. 1699, $\alpha = 4^h53^m3^s$, $\delta = -4°52'.8$
N.G.C. 1700, $\alpha = 4\ 53\ 0$, $\delta = -4\ 59.3$ } (1920); $\lambda = 172°$, $\beta = -26°$

Plate No. 314, 1917, November 18, 120^m. S 27. Large images, fairly round
Plate No. 3 (Hoge), 1919, December 24, 110^m. S 30. Small round images

N.G.C. 1700 has a very bright center fading away in several gradual steps and forming an ellipse $50'' \times 30''$, p 92°. The entire mass is soft, having no detail or structure other than the changes in intensity between center and edge. A 23-hour exposure made with the focal-plane spectrograph on the 60-inch reflector gave a spectrum of sufficient strength to show that the type is Go or later, and that the nebula has large positive radial velocity.

There are two other nebulae on the plate whose positions are given with respect to the nucleus of N.G.C. 1700.

a, N.G.C. 1699, p 6°, d 6'.6, MB, $30'' \times 17''$, p 161°. Almost uniform left-handed spiral, vs B Nu. Position given in N.G.C. is incorrect.
b, 129, 13.6 MF, $15'' \times 10''$, p 9° lbM, vs B Nu.

N.G.C. 2024, Auriga

$\alpha = 5^h37^m49^s$, $\delta = +51°5'.6$ (1920); $\lambda = 174°$, $\beta = -15°$

Plate No. 316, 1917, November 19, 30^m. Cramer Crown. Images large and round

Comparison of this plate with Keeler's photograph, taken June 28, 1902, shows no apparent change in the nebula (*Lick Observatory Publications*, **8**, Plate 13).

N.G.C. 2146, Camelopard

$\alpha = 6^h5^m53^s$, $\delta = +78°23'$ (1920); $\lambda = 102°$, $\beta = +25°$

Plate No. 358, 1919, December 23, 258^m. S 23. Images medium and a little elongated. Illustrated Plate XV*f*

A most remarkable nebula, best described in parts, although actually all blended together. (1) An irregular mass of nebulosity $3'.5 \times 1'$, p 150° greatly differing in intensity, with dark

markings in the direction of its elongation. The nucleus lies a little S of the center of this mass; the nebulosity is brightest around the nucleus. Superimposed on this bright mass is a dark marking in the form of a hand, with four talon-like fingers stretching S*p* and with three stars standing out upon it. (2) A lobe in the form of an elongated ellipse 3′.3×1′, *p* 125°, with greatest density along the periphery. This extends about 1′.4 beyond the S end of (1) and its axis produced would intersect (1) at its N end. The interior is filled with soft nebulosity, has a line of bright knots toward its N end, and some tufts projecting over its *f* side. (3) A spiral arm leaving the N*p* point of (1) and sweeping to the S in such a way as to give the effect of a left-handed spiral. It ends *p* 200°, *d* 2′, with respect to the nucleus.

One might describe the system as a spiral with abnormal center, attached to a single arm or to double arms in the latter case, the lobe forming one of the arms. In the former case a single arm emerges from the S corner of (1), sweeping around the *f* side and under the N end of (1), and emerging on the *p* side as (3). In either case the major axis of the arm or arms would be 5′.2 long and lie in *p* 120°. At the extremities there is the effect of a turn in the arm, but there is no increase in density where the single arm and element (1) are superimposed.

A medium-bright right-handed spiral, 8′×2′, *p* 30° lies *p* 54°, *d* 19′ with respect to nucleus of N.G.C. 2146. The plate shows many small nebulae.

N.G.C. 2245, Monoceros

$\alpha = 6^h 28^m 17^s$, $\delta = +10°13'.2$ (1920); $\lambda = 169°$, $\beta = +2°$

Plate No. 323, 1918, February 14, 60^m. S 27. Poor seeing.
Large round images

Plate No. 329, 1919, March 28, 95^m. S 30. Excellent seeing.
Small round images. Illustrated Plate XVI*a*

A fan-shaped nebula fading away irregularly from an almost stellar point toward the circumference, beyond which extends, torch fashion, nebulosity similar to that of the Orion nebula. A few seconds from its apex and almost at right angles to its axis is a line of nebulosity 30″–40″ long. Alongside this line, away

from the nebula, is a fan-shaped dark area, appearing to be a shadow cast by an opaque portion of the line, the light source being the fan itself. Evidently the whole region is nebulous, as detail can be seen in the shadow, particularly a looped thread formation. The two photographs appear to show a striking difference about the head, but this may be due to the differences in the plates. The 1918 plate shows a round stellar nucleus standing out from the nebulosity, while the 1919 plate shows an almost solid mass completely covering the nucleus. Further observations will be made.

N.G.C. 2247, Monoceros

$\alpha = 6^h 28^m 45^s$, $\delta = +10° 22'.8$ (1920); $\lambda = 169°$, $\beta = +2°$

Plate No. 323, 1918, February 14, 60^m. S 27. Poor seeing. Large round images

Plate No. 329, 1919, March 28, 95^m. S 30. Excellent seeing. Small round images. Illustrated Plate XVI*a*

This nebula lies $9'.9$ N of and $5'.7$ *f* N.G.C. 2245 involving centrally the star B.D.$+10°$ 1172. It surrounds the star irregularly, streamers radiating $2'$ to $3'$ from the center. In addition to the streamers there is a small patch $1'$ N and a line about $1'$ S. Both N.G.C. 2245 and N.G.C. 2247 lie in a dark lane. While Hubble's variable N.G.C. 2261 is related to a variable star, neither of these stars has been mentioned as variable.

The position given in the N.G.C. is not correct. Swift's original description is so exactly like that surrounding B.D.$+10°$ 1172 that there is no question of this being the object. The position given is that of the B.D. star.

N.G.C. 2274, 2275, Gemini

N.G.C. 2274, $\alpha = 6^h 42^m 2^s$, $\delta = +33° 39'.0$
N.G.C. 2275, $\alpha = 6\ 42\ 3$, $\delta = +33\ 41.0$ (1920); $\lambda = 149°$, $\beta = +15°$

Plate No. 313, 1917, November 17, 20^m. Cramer Crown. Poor seeing. Images medium and elongated

Plates Nos. 100–137, 1919, December 19, 30^m. S 23. Images small and comate

N.G.C. 2274. Nebulosity $7''$ diameter, gradually brighter toward the middle, with bright almost stellar nucleus. There is trace of a wing N*p*.

N.G.C. 2275. Nebulosity 10″ diameter, gradually brighter toward the middle, with bright stellar nucleus. There are traces of faint surrounding nebulosity 30″ in diameter.

N.G.C. 2288, 2289, 2290, 2291, and 2294, Gemini

N.G.C. 2288, $\alpha = 6^h 45^m 28^s$, $\delta = +33°29'.1$
N.C.C. 2289, $\alpha = 6\ 45\ 29$, $\delta = +33\ 30.9$
N.G.C. 2290, $\alpha = 6\ 45\ 33$, $\delta = +33\ 27.7$ (1920); $\lambda = 149°$, $\beta = +15°$
N.G.C. 2291, $\alpha = 6\ 45\ 35$, $\delta = +33\ 33.0$
N.G.C. 2294, $\alpha = 6\ 45\ 47$, $\delta = +33\ 33.2$

Plate No. 311, 1917, November 16, 90^m. Cramer Crown. Good plate. Small images

Plate No. 315, 1917, November 18, 70^m; 19, 140^m. Total 210^m. S 27. Poor seeing. Large images. Illustrated Plate XV*a*

This group is mentioned by Lord Rosse in his *Observations* and is shown by the photographs to be composed of spirals with a background of ill-defined nebulae of similar character.

The following is a brief description of all the nebulae on the plates. The positions are referred to the nucleus of N.G.C. 2290.

N.G.C. 2288, p 325°, d 1′.8, MB nebulosity, 7″ diameter. B Nu. almost stellar.

N.G.C. 2289, p 343, d 2′.6, 15″×10″, p 100°. gbM, B almost stellar Nu.

N.G.C. 2290, MF ring 5″ to 15″ wide, broken in places, outside diameter 1′.10×0′.54 and mean diameter 0′.9×0′.45. B stellar Nu. in MB nebulosity 10″ diameter connecting with outer ring. Almost certainly a left-handed spiral.

N.G.C. 2291, p 3°, d 5′.3, B almost stellar Nu. in F, R, nebulosity 35″ diameter showing traces of rings, almost certainly spiral.

N.G.C. 2294, p 28°, d 6′.2, B almost uniform spindle 27″×9″, p 7′.5. Surrounded by faint nebulosity 40″×10″ and having a vs B diffuse elongated Nu.

a,	p 263°, d 16′.2	F	Patch, 8″ diameter.
b,	285	11.9	F	3″ diameter, gbM, Nu.
c,	220	11.7	MB	10″ diameter, gbM, Nu.
d,	349	11.0		Semicircular, 10″ radius, MB on curve, fades back of Nu. From vertex to central Nu. is a bright line 2″ wide, p 137°.
e,	96	5.2	F	Sliver, 10″×5″, p 130°.
f,	95	5.4	F	Spot, 3″ diameter.
g,	108	6.0	F	Diffuse spot, 8″ diameter.

h,	130	8.7	F	20″×5″, *p* 116″, MB Nu. near *f* end.
i,	146	12.9	MB	Nebulous star.
j,	96	7.5	F	15″×10″, *p* 85° elongated diffuse spot.
k,	127	9.4		15″×8″, *p* 32° gbM Nu., looks S-shaped.
l,	67	13.5	F	Diffuse patch, 15″ diameter.

N.G.C. 2359, Canis Major

$\alpha = 7^h13^m50^s$, $\delta = -13°\ 4'.1$ (1920); $\lambda = 197°$, $\beta = 0°$

Plate No. 320, 1917, December 17, 60^m; 18, 150^m. Total 210^m. S 23. Images large and round. Illustrated Plate XVI*b*

The brighter parts of the nebula agree closely with the drawings by the earlier observers. Sir John Herschel pictured it as resembling a bust, while Lassell drew it as like a balloon, with a long neck twisted in the S*p* direction. The balloon or head is approximately 5′ in diameter; the neck is to the S, with nebulosity about 1′ wide extending 8′ *p*, concave on the N and gradually narrowing and fading out. From the top (N) of the head a symmetrical streamer concave to S extends in *p* direction. The radius of curvature of the two streamers is roughly 15′ and their ends are about 8′ apart. A second streamer about 1′ wide extends *f* from the top of the head to a distance of 9′.

N.G.C. 2403,* Camelopard

$\alpha = 7^h29^m7^s$, $\delta = +65°46'.5$, (1920); $\lambda = 118°$, $\beta = +30°$

Plate No. 307, 1917, October 19, 100^m. Cramer Crown. Images small and round

The illustration of N.G.C. 2403 (*Mount Wilson Contribution*, No. 132, Plate X*c*; *Astrophysical Journal*, **46**, 35, 1917, Plate V) was made from Plate No. 307, and not from No. 169 as there stated.

The nebulous spot *p* 50°, *d* 3′.4, with respect to the center of the nebula is probably a flaw, as there is a difference in character between it and the rest of the nebulosity on the plate.

N.G.C. 2537, Lynx

$\alpha = 8^h7^m35^s$, $\delta = +46°14'$ (1920); $\lambda = 141°$, $\beta = +33°$

Plate No. 2968 (Shapley), 1916, March 27, 30^m. S 27
Plate No. 359, 1919, December 23, 60^m. S 30. Images small and elongated

Nebulosity of the form of a horseshoe or a semi-elliptical line, major axis N–S, concave to the S, together with a line of

nebulosity 30″ long lying in the center of the ellipse on the major axis. Two faint lines of nebulosity extend from the N end of this line to the outer nebulosity, the included angle being about 150°. The axes of the complete ellipse would measure 75″×45″. The nebulosity is of the mixed type, there being a number of well-defined knots in it.

I.C.II 2233 falls near the edge of the plates and appears to be a faint edge-on spiral 4′×10″, p 170°±, with faint stellar nucleus. A faint patch 20″ diameter lies 4′.6 f N.G.C. 2357.

N.G.C. 2964, Leo Minor

$\alpha = 9^h38^m11^s$, $\delta = +32°12.8$ (1920); $\lambda = 162°$, $\beta = +50°$

Plate No. 321, 1917, December 18, 60^m. Cramer Crown. Images small and round

Plate No. 324, 1919, February 28, 210^m. S 30. Images small and round

A right-handed spiral, with bright inner arms extending to 75″×45″, p 90°, and exterior arms to 2′.5×1′.2. The inner arms are dotted with bright condensations, the outer are faint and soft. Several peculiar details suggest a drift of the component parts relative to each other; among these may be noted the winged knots on the p side, the disjunction of the nucleus and the f arm, and a left-handed wisp crossing the p arm N of the nucleus.

N.G.C. 2968, Leo Minor

$\alpha = 9^h38^m28^s$, $\delta = +32°17'.7$ (1920); $\lambda = 162°$, $\beta = +50°$

Plate No. 321, 1917, December 18, 60^m. Cramer Crown. Images small and round

Plate No. 324, 1919, February 28, 210^m. S 30. Images small and round

Probably an edge-on spiral, since it shows an irregular ellipse of nebulosity 1′.2×7′, p 31°, gradually increasing in brightness toward the central nucleus 2″ diameter, and has an absorption streak running irregularly along the major axis.

The plate shows many small nebulae; measures were made of 15 with the nucleus of N.G.C. 2968 as a center.

a,	p 305°,	d 13′.4	MB,	uniform ellipse, 7″×3″, p 142°.
b,	247	11.3	MB,	uniform ellipse, 8″×4″, p 140°, sbM.
c,	282	10.0	MF,	uniform, 3″ diameter.

d,	196	9.2	F,	spindle, 20″×6″, *p* 129°, F Nu.
e,	329	2.7	MF,	uniform patch, 9″×4″, *p* 48°.
f,	242	0.8	MB,	10″×2″, *p* 179°, gbM.
g,	4	14.1	MB,	10″ diameter, gbM.
h,	166	6.5	MB,	10″ diameter, *f* side stronger.
i,	168	13.6	MB,	gbM, 11″×8″, *p* 60°.
j,	154	7.7	F,	uniform, 12″×3″, *p* 132°.
k,	61	4.9	MB,	sbM, 12″×6″, *p* 75°.
l,	19	13.0	MF,	spindle, gbM, 10″×4″, *p* 23°.
m,	124	13.7	MF,	nebulous star, 4″ diameter.
n,	56	14.0	F,	uniform, lbM, 10″×3″, *p* 23°.
o,	47	15.9	MF,	gbM, Nu, 10″×3″, *p* 29°.

N.G.C. 2970, Leo Minor

$\alpha = 9^h38^m48^s$, $\delta = +32°20'.7$ (1920); $\lambda = 162°$, $\beta = +50°$

Plate No. 321, 1917, December 18, 60^m. Cramer Crown. Images small and elongated

Plate No. 324, 1919, February 28, 210^m. S 30. Images small and round

Bright nebulosity gradually fading away, 15″×10″, *p* 80°, with a bright stellar nucleus about 5″ diameter centrally located.

N.G.C. 3310, Ursa Major

$\alpha = 10^h33^m48^s$, $\delta = +53°55'.1$ (1920); $\lambda = 124°$, $\beta = +55°$

Plate No. 356, 1919, December 22, 12^m and 90^m. Exp. on same plate. S 30. Images small and round

A left-handed spiral, 90″×50″, *p* 170°. The short exposure shows a bright nucleus surrounded by a bright elliptical ring, 22″×15″, *p* 140°, from which springs an arm of much smaller density in *p* 130°, bending to the north and running for a length of about 25″. A faint star with faint surrounding nebulosity lies just adjoining the ring at *p* 230°, *d* 14″, from the center. The long exposure shows a mass 30″×25″, *p* 130°, with the arm emerging as above and ending at *p* 20°, *d* 25″. The nucleus, ring, and two stars show plainly. There are traces of other arms lying around the bright mass, particularly one emerging opposite the strong arm running southward and ending at *p* 165°, *d* 30″. The ring is strongest in its N and S sections.

N.G.C. 3367, Leo Major

$\alpha = 10^h 42^m 21^s$, $\delta = +14°10'.2$ (1920); $\lambda = 200°$, $\beta = +59°$

Plate No. 289, 1917, April 22, 70^m. S 23. Images small and comate

Plate No. 327, 1919, March 1, 150^m. S 30. Small round images.

Illustrated Plate XV*e*

A left-handed spiral about 1'.8 diameter, almost circular, with a bright sharp stellar nucleus. The periphery is well defined on the *p* side but lacking on the *f*. It is similar in type to N.G.C. 5921[1] in that an almost straight bar crosses the center *p* 70°, from the ends of which emerge arms almost at right angles to the bar, a single arm at one end, a double one at the other. The bar is slightly concave on the N side and its *f* end continues in a series of condensations across the arm to the periphery. The arm emerges from the bar 14″ from the nucleus and turns to the N. The *p* end of the bar spreads into soft nebulosity and just touches the arm from the *f* end; the arm on the *p* end leaves at about 16″ from the nucleus, turns to the south, and at about 10″ spreads into two parallel arms with nebulosity between them, which run parallel for about 90°; the outer one then fades away into the rim, while the inner one continues and is merged in the *p* rim. There are a number of branching and crossing threads, and a bright knot *p* 267°, *d* 47″, from the nucleus lying in the periphery. The greatest extent of the nebulosity is 60″, *p* 40°. The double arm brightens at a point just *f* the nucleus. The plate shows a number of nebulous spots, the more prominent of which are as follows, the measures referring to the nucleus of 3367.

a,	*p* 269°, *d*	14'.4	5″ diameter, uniform.
b,	193	11.0	3″ diameter, gbM, B, stellar Nu.
c,	151	4.9	3″ diameter, stellar Nu.
d,	149	13.0	11″×5″, *p* 126°, gbM.
e,	150	15.0	10″×4″, *p* 145°, lbM.
f,	25	18.1	5″ diameter, gbM.
g,	34	14.3	5″ diameter, lbM.
h,	45	17.7	4″ diameter, lbM.
i,	57	15.3	5″ diameter, gbM.
N.G.C. 3377	49	21.8	

[1] *Publications of the Astronomical Society of the Pacific*, 24, 227, 1912.

N.G.C. 3371	Should lie about one-third the distance from 3367 to 3377, but there is nothing on the plate.
N.G.C. 3373	Should lie in the region *f* 3367 and a little S, but there is nothing on the plate.

N.G.C. 3377, Leo Major

$\alpha = 10^h 43^m 28^s$, $\delta = 14° 24'.4$ (1920); $\lambda = 201°$, $\beta = +60°$

Plate No. 289, 1917, April 22, 70^m. S 23. Small astigmatic images
Plate 327, 1919, March 1, 150^m. S 30. Small comate images

A diffuse ellipse $90'' \times 30''$, *p* 40°, gradually increasing in brightness toward the center, where there is a great increase in brightness in an elongated nucleus $20'' \times 13''$. A number of faint nebulae not listed under N.G.C. 3367 appear in the field. The measures refer to the nucleus of N.G.C. 3377.

a,	*p* 315°, *d*	9'.1	Very faint, 1' diameter.
b,	60	8.2	MF, uniform, 10" diameter.
c,	110	12.9	MF, uniform, $12'' \times 4''$, *p* 129°.
d,	64	19.4	MF, lbM, 8" diameter.
N.G.C. 3391	52	22.9	($10^h 44^m 45^s$, +14° 38'.6) (1920); appears on the corner of plate 289. The image is bright, $20'' \times 11''$; *p* 26°, and suggestive of spiral formation, but the image is too comate to say for certain.

N.G.C. 3379, Leo Major

$\alpha = 10^h 43^m 37^s$, $\delta = +13° 0'.2$ (1920); $\lambda = 203°$, $\beta = +59°$

Plate No. 290, 1917, April 23, 75^m. S 23. Small, slightly elongated image
Plate No. 334, 1919, March 30, 120^m. S 23. Small, slightly elongated image.
Illustrated Plate XVII*a*

A nebula which long since attracted attention, owing to its resemblance to an unresolved star cluster. It has a very bright nucleus $10''$–$12''$ diameter, surrounded by a bright atmosphere, $30''$ diameter, which gradually fades away at $90''$ diameter. The nebula differs from many others, such as N.G.C. 4374 (M 84) and N.G.C. 4402, in having a planet-like nucleus, whereas usually the nebulosity gradually increases toward the center, with a possible sudden increase in brightness to form a semi-diffuse nucleus. A spectrogram[1] made with the focal-plane spectrograph at the

[1] *Publications of the Astronomical Society of the Pacific*, **30**, 255, 1918.

Newtonian focus of the 60-inch reflector shows the nucleus to be G5 or later, and to have a radial velocity of about +850 km/sec. Slipher obtained a value of 780 km/sec. Faint traces of the outer nebulosity show a maximum of continuous spectrum corresponding to the nucleus.

N.G.C. 3384, Leo Major

$\alpha = 10^h44^m4^s$, $\delta = +13°3'.1$ (1920); $\lambda = 203°$, $\beta = +59°$

Plate 290, 1917, April 23, 75m. S 23. Small, slightly comate images
Plate 334, 1919, March 30, 120m. S 23. Small, lightly comate images.
Illustrated plate XVII*a*

An astonishing nebula consisting of a bright center 40″ diameter, on which are superimposed a very bright elongated nucleus 19″×10″, p 45°, crossed by a second bright nucleus 40″×5″, p 130°, presenting a Saturn-like appearance. Finally, from this mass wings or branches extend in p 53° on either side, to a distance of 1′.5 The wings gradually broaden to a width of 1′ at 1′ from the center, where they are rounded off.

The three nebulae, N.G.C. 3379, 3384, 3389, appearing on the same plate present very different features. N.G.C. 3389 is a well-defined spiral, N.G.C. 3384 presents spiral and planetary characteristics, while N.G.C. 3379 leads one to believe it a very distant, unresolved cluster or group of spirals.

N.G.C. 3389, Leo Major

$\alpha = 10^h44^m14^s$, $\delta = +12°57'.0$ (1920); $\lambda = 204$, $\beta = +60°$.

Plate No. 290, 1917, April 23, 75m. S 23. Small slightly comate images
Plate No. 334, 1919, March 30, 120m. S 23. Small slightly elongated images. Illustrated Plate XVII*a*

A medium-bright right-handed spiral 110″×52″, p 107°, having a very small stellar nucleus. The arms are fairly dense, with condensations along them, but are not strictly regular in form.

N.G.C. 3395–3396, Leo Minor

N.G.C. 3395, $\alpha = 10^h45^m23^s$, $\delta = +33°24'.4$
N.G.C. 3396, $\alpha = 10\ 45\ 28$, $\delta = +33\ 24.9$ (1920); $\lambda = 160°$, $\beta = +64°$

Plate No. 286, 1917, March 26, 120m. S 23. Small round images.
Illustrated Plate XVIII*a*
Plate No. 332, 1919, March 29, 110m. S 30. Small round images

N.G.C. 3395 is a right-handed spiral with its major axis in *p* 32°. Its S*p* portion is well defined and extends about 52″ along the major axis from the nucleus. The N*f* portion is markedly deficient in size and in density of material. N.G.C. 3396 lies *p* 66°, *d* 73″ N*f* with respect to the nucleus of 3395. It is composed of a bright elongated nucleus 10″×5″, *p* 97°, with which is blended a knot about 3″ diameter 9″ *f* and a short line diagonally opposite. Surrounding this is a mass whose general axis is in *p* 94° and which extends 42″ *f* the nucleus. Between the two nebulae is evidence of a great disturbance, since material which would ordinarily belong to the N*f* arm of 3395 is absent, while stream lines indicate its presence about 3396. It remains to be ascertained whether the formation is the result of two separate centers or whether 3395 has separated from 3396, or, finally, whether 3396 has wrenched material away from 3395. The stream line of 3395 suggests a right-hand twist. There is more than enough material in 3396 to make up for that lost in the arm of 3395; in fact, it is just about equal to the complete arm of 3395.

There are many small nebulae on the plates, the more prominent of which are the following, the measures referring to the nucleus of N.G.C. 3395:

I.C.II 2603			Not on plates.
a,	*p* 278°, *d* 15′.9		10″×4″, *p* 56°, bM.
Big. 270			Not on plates.
b,	280	11.1	MF, 5″ diameter, bM.
c,	210	15.2	MF, 10″×5″, *p* 99°, lbM.
I.C.II 2604	203	13.8	MB, Irr. R, 50″ diameter, RH spiral.
d,	339	11.9	MF, 6″ diameter, lbM.
e,	330	4.3	MF, 6″ diameter, lbM.
f,	342	5.4	MB, 2″ diameter, stellar.
I.C.II 2605 Big. 402			Part of arm of N.G.C. 3395.
I.C.II 2608	157	14.1	MB, 45″×6″, *p* 118°, B Nu., spindle.
g,	40	13.0	MB, 10″ diameter, lbM.
h,	98	9.2	MF, 3″ diameter, lbM.
i,	46	17.4	MF, 4″ diameter, lbM.
j,	80	12.7	F, 9″×5″, *p* 116°, lbM.
k,	124	23.2	MB, 60″×10″, *p* 170°, B Nu., spindle.

N.G.C. 3786, 3788, Ursa Major

N.G.C. 3786, $\alpha = 11^h 35^m 29^s$, $\delta = +32° 21'.3$
N.G.C. 3788, $\alpha = 11\ 35\ 32$, $\delta = +32\ 22.8$ (1920); $\lambda = 159°$, $\beta = +75°$

Plate No. 337, 1919, April 29, 30^m. S 23. Images small and slightly elongated

Plate No. 338, 1919, April 29, 135^m. S 27. Images large and fairly round. Illustrated Plate XV*b*

N.G.C. 3786 is a right-handed spiral with a bright nucleus, a fairly bright central part 60″×30″, *p* 67°, and a faint interrupted ring, not strictly elliptical, 2′×1′, *p* 75°, which is probably an extended arm. The central part is weaker on the N side, which shows an irregular dark marking. The outer ring just touches a faint prolongation from the S end of N.G.C. 3788.

N.G.C. 3788 is a right-handed elliptical spiral 92″×20″, *p* 179°, very similar to N.G.C. 5545 lying *p* 18°, *d* 1′.4 N*f* N.G.C. 3788. The nebulosity on and between the arms is soft, with traces of condensation near the center. The brightest spot is a knot *p* 40°, *d* 10″. The center and the N end of the major axis in the curve of the arm are bright.

N.G.C. 3791 and 3793 do not appear on the plates. Plate No. 338 is literally covered with small nebulae, some of them spindles, and many of them merely rounded masses with relatively bright ill-defined centers. Presumably these are related to the spiral family. The measures of some of them, referred to the nucleus of N.G.C. 3786, are as follows:

a,	*p* 314°,	*d* 22′.4	MF, R, 7″, lbM.
b,	311	16.6	F, 9″×4″, *p* 135°.
c,	285	12.4	F, Irr. R, 6″.
d,	273	11.0	MF, R, 7″, lbM.
e,	330	17.4	MF, R, 4″, lbM.
f,	325	14.4	MB, R, 5″, BM.
g,	331	16.7	F, Irr. R, 8″.
h,	336	18.5	MB, R, 7″, BM.
i,	331	14.9	F, Irr. R, 6″, lbM.
j,	322	11.4	MF, R, 5″, bM.
k,	238	6.1	MF, Irr. R, 9″, lb near end.
l,	226	4.8	MF, 20″×4″, *p* 132°, knots at middle and ends.
l′,	225	4.7	MB, 8″×3″, *p* 87°, other F nebulosity *f*.

m,	285	2.9	F, Irr. R, 6″, uniform.
n,	351	16.0	MF, R, 5″, bM.
o,	210	1.4	MB, 10″×3″, *p* 139°, BM.
p,	181	10.5	MF, R, 6″, lbM.
q,	6	8.4	MB, R, 6″, bM.
r,	167	8.5	MF, R, 5″, lbM.
s,	10	11.4	MF, R, 4″, bM.
t,	70	4.6	MF, 14″×4″, *p* 3°, bM, spindle.
u,	44	10.7	MF, R, 4″, lbM.
v,	115	8.6	F, Irr. R, 4″, lbM.
w,	34	15.0	MF, 10″×2″, *p* 135°, lbM.
x,	115	11.4	F, In R, 6″, lbM.
y,	60	12.4	F, R, 2″.
z,	112	15.3	MF, Irr. R, 10″, uniform.

N.G.C. 4395, 4399, 4400, 4401, Canes Venatici

N.G.C. 4395, $\alpha = 12^h 21^m 51^s$, $\delta = +33° 59'.4$
N.G.C. 4399, $\alpha = 12\ 22\ \pm$ $\delta = +34\ 0\pm$
N.G.C. 4400, $\alpha = 12\ 22\ \pm$ $\delta = +34\ 0\pm$
N.G.C. 4401, $\alpha = 12\ 22\ 1$ $\delta = +33\ 57.5$
(1920); $\lambda = 121°$, $\beta = +82°$

Plate No. 330, 1919, March 28, 270^m. S 23. Images small and elongated
Plate No. 331, 1919, March 28, 20^m. S 30. Images small and round
Plate No. 333, 1919, March 29, 30, 450^m. S 30. Images small and slightly elongated. Illustrated Plate XVII*b*

These four nebulae, together with a large amount of fainter nebulosity, form a remarkable spiral. The configuration is approximately circular in outline, with indications of a three-armed spiral or pinwheel and a two-armed spiral with one detached arm (similar to N.G.C. 3395–3396), all of which are blended and not simply superimposed. The brightest nebulosity is not at the center of either, but lies in the S*f* portion of the whole. Aside from these predominating features, large faint whorls are also seen which indicate that the nebula is roughly spherical in form. N.G.C. 4395 is the two-armed portion, N.G.C. 4399 the S*f* arm of the pinwheel, and N.G.C. 4401 the brightest knot of the whole. The nebula as a whole is roughly 12′×10′, elongated in *p* 128°, with N.G.C. 4395 as center; beyond this, and in fact scattered over the plate, are many small nebulous stars or spots similar to those within the

nebula. The plates are not strong enough to show definitely the relation of the component parts, and further descriptions will be reserved for a longer exposure.

N.G.C. 4656–4657, Canes Venatici

N.G.C. 4656, $\alpha = 12^h 40^m\ 5^s$, $\delta = +32°36'.2$
N.G.C. 4657, $\alpha = 12\ 40\ 14$, $\delta = +32\ 39.4$ } (1920); $\lambda = 90°$, $\beta = +86°$

Plate No. 336, 1919, April 28, 20^m. S 27. Images comate
Plate No. 339, 1919, April 29, 140^m. S 27. Images medium and elongated
Plates Nos. 100–145, 1920, February 16, 240^m. S 30. Images small and round. Illustrated Plate XVIII*b*

The objects listed as N.G.C. 4656 and 4657 constitute a most interesting single right-handed spiral. It appears as though a section were scaling off from a streamer of nebulosity which extends across the plate for a distance of 20′. The nebulosity strongly resembles that of N.G.C. 4449. There is no well-defined center or nucleus, but the inner end of the stronger arm is relatively bright, and this is taken as the center in the discussion. The strong N*f* arm consists of well-defined soft nebulosity dotted with about 50 condensations and having much fainter material lying on its concave side. The position angle at the center is about 26°, but the direction changes rapidly, the arm becomes concave on the *f* side and turns south at *p* 50°, *d* 3′.6 from the center, and after a return of 25″ stops. The width is from 20″ to 30″. The S*p* arm is not as well defined and the material is distributed in several bands. It consists of a *p* member emerging from the center in *p* 220° to a distance of 3′.4, which then branches, one branch continuing straight on, the other curving slightly concave N for a distance of 5′. The second member starts in *p* 185°, runs straight for 2′, then gradually curves for about 5′, ending in *p* 223°. There are traces of other lines of material extending to a distance of 8′.

In addition to a number of very small nebulae on the plate there is a well-defined two-armed right-handed spiral *p* 260°, *d* 3′.4 with respect to the center of 4656–7; it is 30″×20″, *p* 10°.

N.G.C. 5257, 5258, Virgo

N.G.C. 5257, $\alpha = 13^h 35^m 49^s$, $\delta = +1° 14'.7$
N.G.C. 5258, $\alpha = 13\ 35\ 53$, $\delta = +1\ 14.3$ (1920); $\lambda = 298°$, $\beta = +61°$

Plate No. 345, 1919, June 27, 50m. S 30. Images small and elongated. Illustrated Plate XIX*b*

N.G.C. 5257 is a left-handed spiral with two principal arms, each making a complete revolution before fading out. It forms an irregular ellipse $80'' \times 40''$, p 120° (no trail). For a length of $20''$, beginning a half-turn from the center, there are several bright knots in line in each arm. Beyond this the nebulosity is soft and spreads into brushes at the ends. The curvature at the ends is very small, and there is indication that the f one extends to N.G.C. 5258.

N.G.C. 5258 is a left-handed spiral whose brighter parts lie within an ellipse $60'' \times 18''$, p 30° (no trail), from the extremities of which spring the two main opposite arms forming a letter **S**, the arms themselves being opposite arcs of a circle of $30''$ radius. The central nucleus is brighter than that of N.G.C. 5257, and two knots as bright as the nucleus lie one to the N end and one to the S. The arms are soft and brushy, as in N.G.C. 5257.

N.G.C. 5278–5279, Ursa Major

N.G.C. 5278, $\alpha = 13^h 38^m 40^s$, $\delta = +56° 4'.3$
N.G.C. 5279, $\alpha = 13\ 38\ 45$, $\delta = +56\ 4.5$ (1920); $\lambda = 74°$, $\beta = +60°$

Plate No. 341, 1919, May 28, 30m. S 30. Fair images
Plate No. 342, 1919, June 25, 160m. S 30. Fair images. Illustrated Plate XIX*a*

These separately listed objects are parts of the same nebula, consisting of a stellar center and a ribbon of nebulosity which encircles the nucleus for a little more than one turn, then abruptly decreases in intensity and widens out, and continuing in a curve, concave to the S, ends abruptly in a bright twist or hook, at about p 70°, d $40''$. The first coil is roughly $30'' \times 20''$, p 60°, and the whole lies within an ellipse $65'' \times 30''$, p 60°. The curl on the end forms a semicircle of about $7''$ radius and points p 320°.

This nebula appears on the same plates as the group of objects listed by Barnard under I.C. 917 to 928; the illustration is from Plate No. 342 where it appears near the edge.

N.G.C. 5544,* 5545,* 5557, Boötes

N.G.C. 5544, $\alpha = 14^h13^m40^s$, $\delta = +36°56'.5$
N.G.C. 5545, $\alpha = 14\ 13\ 41$, $\delta = +36\ 56.8$
N.G.C. 5557, $\alpha = 14\ 15\ 5$, $\delta = +36\ 51.6$
(1920); $\lambda = 32°$, $\beta = +68°$

Plate No. 127, 1912, June 13, 180^m. S 23
Plate No. 260, 1916, April 30, 50^m. S 23. Images small and round
Plate No. 261, 1916, May 1, 2, 3, 4, 5, 360^m. S 27. Images small. Illustrated Plate XX*b*

In *Mount Wilson Contribution*, No. 132, the orientation of these plates is in error 180°, consequently the descriptions of N.G.C. 5544 and 5545 are interchanged and Plate XIII*c* is shown S at top and *f* at right. The positions in N.G.C. are incorrect, as that of 5545 is S of 5544, while actually it is to the N. Bigourdan's value (*Annales Observatoire de Paris, Observations*, 1899) for N.G.C. 5544 is $\alpha = 14^h12^m50^s.62$, $\delta = +37°2'7''.2$ (1900), the relative position of the nebulae *p* 244°±, *d* 37″, but he states that the measures are uncertain and difficult. The corrected description is as follows:

N.G.C. 5544 and 5545 are two overlapping spirals, the former in plan, the latter very much inclined to the line of sight.

N.G.C. 5544 consists of a bright stellar nucleus, a nebular ring about 5″ wide and 28″ outside diameter, a fainter diametral streak crossing the nucleus in *p* 130° and an outer ring of about the same intensity as the inner one, irregularly round, 8″ wide and 45″ outside diameter; both rings are slightly elongated in *p* 115°. The nebulosity is entirely soft.

N.G.C. 5545 is a left-handed spiral 70″×15″, *p* 60°, its *p* end just tangent to the *f* point of the nucleus of N.G.C. 5544. The nucleus is faint and stellar. The arms are about equal in intensity where they start from the nucleus, but that on the *p* side continues bright for a much greater distance, being interrupted, however, at several points. Several knots and condensations

appear. Its extremely small, bright nucleus lies in *p* 68°, *d* 36″, with respect to nucleus of N.G.C. 5544.

N.G.C. 5557 appears at the *f* side of the plates; it is so distorted that one cannot more than suspect it to be a spiral. Its position with respect to N.G.C. 5544 is *p* 105°, *d* 17.4 and, allowing for distortion, seems to be a bright mass 18″×14″ surrounded with fainter nebulosity 40″ diameter.

The plates are covered with a multitude of faint nebulae, a number of which are as follows, their positions being given with respect to the nucleus of N.G.C. 5544:

a,	*p* 235°,	*d* 20′.7	MB, Irr. R, 12″ diameter BM (edge of plate).
b,	216	21.3	F, nebulous spot, 5″ diameter (edge of plate).
c,	329	9.8	F, uniform sliver, 20″×2″, *p* 24°.
d,	205	7.5	MB, elongated Nu., 4″×2″, *p* 4°, in MF nebulosity, 11″ diameter.
e,	228	3.8	F, 5″ diameter, gbM.
f,	356	6.6	Faint, MF at center, 10″×3″, *p* 42°.
g,	179	4.8	Bright Nu., 2″ to 3″ diameter, surrounded by F nebulosity, 13″ diameter, *p* 79.
h,	173	16.1	MF center, 10″×2″, *p* 145°, in F nebulosity 15″×5″.
i,	23	7.8	Two F slivers each 11″ long lying *p* 37° and 52° intersecting to form a V on S*p* end.
j,	139	18.5	F, 8″ diameter, gbM.
k,	97	13.0	F, 10″×2″, *p* 130°.
l,	124	16.0	F, Wisp, 13″×3″, *p* 76°.
m,	130	23.1	Nebulous spot, 10″×5″, *p* 51° (edge of plate).

N.G.C. 5868, 5869, Serpens

N.G.C. 5868, $\alpha = 15^h 5^m 44^s$, $\delta = +0°50'.2$
N.G.C. 5869, $\alpha = 15\ 5\ 45$, $\delta = +0\ 46.6$
(1920); $\lambda = 328°$, $\beta = +47°$

Plate No. 328, 1919, March 1, 50^m, S 23. Images small and almost round

Plate No. 335, 1919, March 30, 30^m, S 30. Images small and elongated

N.G.C. 5868 is a medium bright, semi-diffuse stellar nucleus 2″–3″ diameter with a faint halo 5″ diameter.

N.G.C. 5869 is a medium bright, diffuse stellar nucleus 5″×4″, *p* 133°, surrounded with nebulosity gradually fading away at 10″×7″.

N.G.C. 5865 and N.G.C. 5871, for which positions are given in this vicinity, do not appear on the plates.

There is a very faint diffuse spot roughly 7″ diameter, p 116°, d 1′.9, with respect to the nucleus of 5868.

N.G.C. 6014, 6017, Serpens

N.G.C. 6014, $\alpha = 15^h52^m\ 1^s$, $\delta = +6°\ 9'.7$
N.G.C. 6017, $\alpha = 15\ 53\ 19$, $\delta = +6\ 13.6$ (1920); $\lambda = 341°$, $\beta = +39°$

Plate No. 325, 1919, February, 28, 30^m. S 30. Images small and slightly elongated

N.G.C. 6014. Medium bright stellar nucleus lying centrally in faint nebulosity 30″ diameter, showing traces of rings. It is probably a spiral. There is a faint nebula of the same character, 15″ diameter, at p 51°, d 11′.0, with respect to N.G.C. 6014.

N.G.C. 6017. A faint elliptical nebula 18″×6″, p 133°, with bright nucleus 7″×5″.

N.G.C. 6703,* Lyra

$\alpha = 18^h45^m0^s$, $\delta = +45°27'.7$ (1920); $\lambda = 42°$, $\beta = +18°$

Plate No. 344 (Duncan and Hoge), 1919, June 26, 315^m. S 30. Images medium and elongated

This plate was taken for classification, but the results are not conclusive and the type must be settled spectroscopically. The nucleus is lost in the very strong central part, 30″ in diameter. The ring, 80″ diameter, shows more plainly, and there is nebulosity between the ring and the central mass; but it is not clear whether the nebula is a planetary or a spiral in plan. Ten small faint nebulae, in addition to the six mentioned previously, are shown on the plate.

N.G.C. 6820, Vulpes

$\alpha = 19^h39^m3^s$, $\delta = +22°53'.3$ (1920); $\lambda = 27°$, $\beta = -1°$

Plate No. 298, 1917, July 23, 90^m. S 23. Images small and nearly round

The nebula lies in a rich region of the Milky Way. It has a stellar nucleus lying eccentrically to the south in a mass of soft, irregular, patchy nebulosity, roughly 30″ in diameter.

N.G.C. 6823, an open cluster, appears on the Nf corner of the plate.

N.G.C. 6846, Cygnus

$\alpha = 19^h53^m22^s$, $\delta = +32°8'.4$ (1920); $\lambda = 37°$, $\beta = +1°$

Plate No. 295, 1917, July 20, 150^m. S 23. Images small and elongated

A small group of twelve stars, approximate magnitude 17, in a very rich region of the Milky Way, clustered about three stars of magnitude 15.

N.G.C. 6888, Cygnus

$\alpha = 20^h9^m33^s$, $\delta = +38°9'.1$ (1920); $\lambda = 43°$, $\beta = +1°$

Plate No. 299, 1917, August 21, 60^m. S 23. Images small and slightly elongated

Plate No. 301, 1917, August 22, 60^m. S 27. Images small and slightly elongated

Plate No. 348, 1919, July 25, 300^m. S 30. Images medium. Illustrated Plate XX*c*

A network nebula in the heart of the Milky Way, about 13° N*p* N.G.C. 6960 and 6992, which it resembles in shape and character of nebulosity. It is roughly elliptical, $18' \times 9'$, *p* 42°. The N, N*p*, and S*p* edges include the bulk of the nebulosity, which gives it a crescent form, the bowl of which is filled with faint and scattered nebulosity.

N.G.C. 6906, Sagitta

$\alpha = 20^h19^m36^s$, $\delta = +6°12'.3$ (1920); $\lambda = 18°$, $\beta = -18°$

Plate No. 352 (Benioff), 1919, August 27, 120^m. Images small and nearly round

A right-handed spiral lying at the edge of the Milky Way where the star density, for this plate, is five to six stars per square minute of arc. The nebula measures $90'' \times 35''$, *p* 35°, the arms are soft and delicate, though increased exposure may show parts to be granular. A short line $12''$ long projects equally beyond the nucleus in *p* 165° and 345°.

N.G.C. 6927, 6928, 6930, Delphin

N.G.C. 6927, $\alpha = 20^h28^m46^s$, $\delta = +9°38'.6$
N.G.C. 6928, $\alpha = 20\ 28\ 58$, $\delta = +9\ 39.2$
N.G.C. 6930, $\alpha = 20\ 29\ 7$, $\delta = +9\ 34.6$
(1920); $\lambda = 22°$, $\beta = -18°$

Plate No. 347 (Duncan and Hoge), 1919, June 27, 60^m. Images small and elongated

Plate No. 350, 1919, August 21, 140^m. S 23. Images small and elongated

These plates show three N.G.C. nebulae in addition to the several small nebulae given below. The foregoing positions have been corrected from Bigourdan's observations.

The following measures refer to the brightest spot of N.G.C. 6928.

a,	*p* 231°, *d*	4′.2	10″×5″, *p* 20°, gbM, BM.
N.G.C. 6927	257	3.0	18″×8″, *p* 10°, gbM, BM.
N.G.C. 6928			100″×28″, *p* 110°, left-handed spiral, two arms making about three-fourths of a turn each. Brightest in the middle where the two arms join with a slight offset, forming a bent line 35″ long.
b,	161	1.6	MF, nebulous spot, 4″ diameter.
N.G.C. 6930	146	3.9	30″×12″, *p* 9°, left-handed spiral nebula with slight traces of outside arms at end of major axis.
c,	139	5.6	Nebulous spot, 3″ diameter.
d,	126	13.2	20″×6″, *p* 70°, lbM.

N.G.C. 7023, Draco

$\alpha = 21^h 0^m 37^s$, $\delta = +67°51'$ (1920); $\lambda = 72°$, $\beta = +14°$

Plate No. 343, 1919, June 25, 160^m. S 23. Images small and slightly elongated

Comparison of this plate with No. 12 (1911, July 23, 149^m, S 23) in the stereocomparator gave no indication of change.

N.G.C. 7048, Cygnus

$\alpha = 21^h 11^m 23^s$, $\delta = +45°57'.4$ (1920); $\lambda = 57°$, $\beta = -2°$

Plate No. 296, 1917, July 20, 60^m. S 23. Images round and large

A planetary resembling the Dumb-bell nebula, about 1′ diameter, weak axis in *p* 170°. The central star is very faint. A longer exposure is necessary to bring out the detail.

N.G.C. 7240, 7242, Lacerta

N.G.C. 7240, $\alpha = 22^h 11^m 53^s$, $\delta = +36°52'.7$
N.G.C. 7242, $\alpha = 22\ 12\ 10$, $\delta = +36\ 53.7$
(1920); $\lambda = 59°$, $\beta = -17°$

Plate No. 292, 1917, June 21, 22, 195^m. S 23. Images round and medium
Plate No. 354, 1919, December 22, 50^m. S 23. Images round and small
Plate No. 357, 1919, December 23, 145^m. S 23. Images small and elongated

A group including twenty in addition to the six nebulae described by Barnard in *A.N.*, **137**, 717, 1906. The measures refer to the nucleus of N.G.C. 7242.

N.G.C. 7240 *p*	0°*d*	0.′	18″×5″, *p* 108°, gbM, B stellar Nu., Barnard *c*.
N.G.C. 7242	73	3.6	12″×6″, *p* 33°, gbM, B stellar Nu., Barnard *a*.
a,	217	8.7	MB, 9″×1.″5, *p* 178°, gbM.
b, I.C.II 5191?	287	4.1	Spindle, 45″×6″, *p* 66°, BNu., Barnard *f*.
c,	214	6.0	F, 3″ diameter
d,	203	8.2	F, 8″×2″, *p* 170°.
e,	217	3.6	B, 3″ diameter, almost stellar, F wings *p* 58°.
f, I.C.II 5192?	251	1.8	12″×6″, *p* 160°, gbM, Barnard *d*.
g,	193	6.5	F, 2″ diameter, bM.
h, I.C.I 1441	332	1.4	Spiral, 30″×15″, *p* 40°, Barnard *e*, Bigourdan 233.
i,	171	4.6	F, 4″×2″, *p* 140°.
j,	4	9.7	F, 10″×2″, *p* 143°.
k,	15	4.1	MB, 4″ diameter, stellar.
l,	175	14.0	MB, 3″ diameter.
m,	95	2.3	F, 2″ diameter.
n,	157	6.2	Spindle, 20″×6″, *p* 120°, B stellar Nu.
o,	141	4.1	F, 6″×3″, *p* 100°.
p, I.C.II 5195	71	4.0	B, 4″ diameter, gbM, almost stellar.
q,	140	5.7	F, 3″ diameter, Nu.
r, I.C.II 5194?	119	4.8	10″ diameter, gbM, B stellar Nu., Barnard *b*.
s,	41	6.3	F, 3″ diameter.
t,	68	7.3	B, 3″ diameter, almost stellar.
u,	40	15.4	F, 20″×6″, *p* 124°, B stellar Nu.
v,	51	12.5	F, 2″ diameter.
w,	83	10.0	F, 2″ diameter.
x,	117	13.6	18″×5″, *p* 118°, stellar Nu.

N.G.C. 7435, 7436, Pegasus

N.G.C. 7435, $\alpha = 22^h 54^m 6^s$, $\delta = +25°42.'2$
N.G.C. 7436, $\alpha = 22\ 54\ 6$, $\delta = +25\ 43.3$ } (1920); $\lambda = 62°$, $\beta = -31°$

Plate No. 293, 1917, June 23, 120^m. S 23. Images small and round

The plate shows a rich field of small nebulae consisting of elongated masses with bright almost stellar nuclei. They are probably spiral.

N.G.C. 7431, $\alpha = 22^h 53^m 47^s$, $\delta = +25°44.'2$ (1920), is a star with faint companion *f*.

N.G.C. 7433, $\alpha = 22^h\ 54^m\ 2^s$, $\delta = +25°43.'2$ (1920), does not appear on the plate.

N.G.C. 7436 has a bright stellar nucleus surrounded by faint nebulosity, 7″ diameter.

The positions of the following nebulae are referred to N.G.C. 7436.

a,	*p* 239°,	*d* 14′.9	MB, 20″×8″, *p* 40°, lbM.
b,	273	7.9	F, 15″×5″, *p* 150, lbM.
c,	249	7.2	MB, 30″×8″, *p* 140, spindle, bM.
d,	332	12.6	F, 15″×10″, *p* 30, lbM.
e,	238	5.7	F, 20″×10″, *p* 150, lbM.
f,	334	5.8	MF, 10″×5″, *p* 150, spindle, stellar Nu.
g,	313	3.5	MF, 5″ diameter, stellar Nu.
h,	300	1.6	MB, 30″×10″, *p* 45, ellipse, stellar Nu.
i,	232	1.0	MB, 30″×10″, *p* 160, spiral, stellar Nu.
j,	187	2.4	MB, 5″ diameter.
k,	270	0.4	B, 20″×6″, *p* 95, spindle, stellar Nu.
l,	168	1.1	MF, 4″ diameter stellar nucleus, N.G.C. 7435.
m,	136	7.3	MB, 20″×10″, *p* 130.
n,	141	9.4	F, 30″×8″, *p* 40, uniform.
o,	47	8.9	MF, 6″ diameter, bM.

N.G.C. 7611, 7615, 7617, 7619, 7621, 7623, 7626, 7631, Pegasus

N.G.C. 7611, $\alpha = 23^h 15^m 33^s$, $\delta = +7° 22'.5$
N.G.C. 7615, $\alpha = 23\ 15\ 53$, $\delta = +7\ 58.5$
N.G.C. 7617, $\alpha = 23\ 16\ 2$, $\delta = +7\ 43.7$
N.G.C. 7619, $\alpha = 23\ 16\ 12$, $\delta = +7\ 46.0$
N.G.C. 7621, $\alpha = 23\ 16\ 20$, $\delta = +7\ 55.7$
N.G.C. 7623, $\alpha = 23\ 16\ 27$, $\delta = +7\ 57.5$
N.G.C. 7626, $\alpha = 23\ 16\ 39$, $\delta = +7\ 46.7$
N.G.C. 7631, $\alpha = 23\ 17\ 24$, $\delta = +7\ 46.7$
(1920); $\lambda = 56°$, $\beta = -51°$

Plate No. 351, 1919, August 21, 130^m. S 23. Images small and round

N.G.C. 7611, B, stellar Nu., 10″ diameter in F nebulosity. 60″×15″, *p* 140°, edge of plate.
N.G.C. 7615, MF, uniform, 40″×20″, *p* 140°.
N.G.C. 7617, B, stellar Nu., 8″×5″, *p* 32°.
N.G.C. 7619, B, Nu., 12″×10″, *p* 32°, in F nebulosity.
N.G.C. 7621, Stellar Nu., 3″ diameter in nebulosity 20″×5″, *p* 170°.
N.G.C. 7623, B, stellar Nu., 8″×6″, *p* 170°, in F nebulosity 15″ diameter.
N.G.C. 7626, B, stellar Nu., 8″ diameter, in F nebulosity 40″ diameter.
N.G.C. 7631, MF, stellar Nu., 3″ diameter, in F nebulosity 90″×30″, *p* 80°.

There are many other small nebulae on the plate, which will be listed when a duplicate plate has been made.

N.G.C. 7722, Pegasus

$\alpha = 23^h34^m41^s$, $\delta = +15°31'.0$ (1920); $\lambda = 68°$, $\beta = -44°$

Plate No. 353, 1919, August 27, 27^m. S 23. Images small, almost round

The exposure is sufficient to show a spiral with bright nucleus and strong absorption streak *f* the nucleus. The portion shown on the plate covers $45'' \times 30''$, *p* 150° (no trail).

I.C.I 922, 928, 931, Ursa Major, and a Group of 72 Others

I.C.I 922, $\alpha = 13^h40^m17^s$, $\delta = +56°0'.4$
I.C.I 928, $\alpha = 13\ 40\ 43$, $\delta = +56\ 1.2$
I.C.I 931, $\alpha = 13\ 40\ 49$, $\delta = +56\ 1.3$
(1920); $\lambda = 73°$, $\beta = +59°$

Plate No. 341, 1919, May 28, 30^m. S 30. Fair images
Plate No. 342, 1919, June 25, 160^m. S 30. Fair images

Barnard originally called attention to this group in *A.N.*, **125**, 379, 1890, and numbers from 917 to 938 (with a few exceptions) were assigned to it in the *Index Catalogue*. Of the seventy-five nebulae shown on the plates only three (not including N.G.C. 5278–5279, which appear among them) have been identified, namely, I.C.I 922, 928, 913. Many of the objects are almost stellar, but they have been listed because of some peculiarity of appearance which distinguishes them from the neighboring star images. Measurements were made on the plate relative to B.D.+56° 1677, for which the reduced co-ordinates are $\alpha = 13^h37^m19^s.6$, $\delta = +56°25'.2$ (1860). Positions are given for right ascension and declination 1860. Hubble's paper[1] on this field which has just been published identifies twenty-five of the objects given here; they are indicated as H22, etc.

[1] E. P. Hubble, "Photographic Investigations of Faint Nebulae," *Publications of the Yerkes Observatory*, **4**, Part II, 1919.

Description		α 1860	δ 1860
MB, Spindle, 30″×9″, *p* 10°, lbM		13h36m 7s.0	+56°22′.4
MF, 7″, gbM	H22	9.1	15.9
B, 14″×8″, *p* 70°		11.6	20.4
MB, 7″, gbM		19.6	25.5
B, Nucleus, N.G.C. 5278		27.2	22.0
B, Tail, N.G.C. 5279		31.5	22.2
MF, 10″, patch	H31	47.3	28.8
MB, 5″		52.5	36.3
MF, 5″, lbM		56.7	36.0
F, 10″, patch		37 4.6	8.9
MF, 5″, lbM		5.6	19.9
MF, 12″ diameter, patch		13.0	40.6
MB, 12″×8″, *p* 135°, spindle, gbM		13.7	31.1
F, 6″, lbM		14.1	14.7
MB, 10″, gbM	H34	14.1	8.9
MF, 20″×5″, *p* 170°, uniform		16.7	31.2
B, B.D.+56° 1677		19.6	25.2
MF, 12″×8″, *p* 100°, lbM	H35	21.9	14.0
MF, 12″×8″, *p* 70°, lbM		23.2	10.2
MB, 4″		23.5	15.9
B, 20″×8″, *p* 100°, gbM	H36	26.1	13.8
MB, 12″×8″, *p* 135°, gbM	H37	34.3	12.6
MF, 4″		38.7	24.8
B, 6″, stellar	H40	45.1	17.8
F, 8″, patch		46.9	10.2
MF, 10″, lbM		47.1	40.1
MB, 10″, patch		48.2	35.1
MB, 12″×4″, *p* 60°, uniform		48.5	33.0
MB, 8″×4″, *p* 135°, lbM	H41	52.0	22.0
MF, 5″, lbM		53.7	26.8
MB, 5″, lbM		54.6	17.4
MB, 8″, I.C.I 922, gbM	H42	38 02.7	18.6
B, 5″, gbM	H43	3.4	17.7
MB, 20″×5″, *p* 100°, spindle, gbM	H44	5.4	18.5
F, 5″, patch		7.5	13.7
MF, 5″, lbM		8.9	17.4
B.D.+56° 1679		14.8	19.7
B, 5″, stellar		16.0	28.1
F, Patch 8″		16.0	14.7
MF, Patch 8″		19.0	14.6
MB, 10″×4″, *p* 90°, patch		26.1	16.7
MB, 3″		28.0	20.4
B, 8″×4″, *p* 120°, gbM, I.C.I 928		29.2	19.4
MF, 6″, gbM		32.0	24.8
MF, 8″, patch		32.7	16.7
MB, 10″×8″, *p* 90, lbM		33.0	25.3
B, 5″, I.C.I 931, stellar	H48	34.8	19.5
MB, 7″×3″, *p* 30°, lbM		35.2	30.4
B, 4″, almost stellar	H49	35.5	20.3
B, Star?		36.6	15.8
B, Star? 4″	H51	37.3	15.6
MF, 10″×4″, *p* 140°, lbM		38.9	24.3
B, 5″, almost stellar		39.4	18.9
B, 6″, almost stellar	H53	41.4	20.3
MB, 4″, almost stellar		42.7	20.9
F, 7″, lbM		43.1	15.0

Description		α 1860	δ 1860
F, 8″×4″, *p* 95°	.....	13h38m47ˢ.2	+56°19′.4
F, 10″×5″, *p* 135°	H56	51.0	15.5
B.D.+56° 1682	.....	56.4	19.6
B, 8″×5″, *p* 40°, gbM	.....	58.9	25.4
B, 15″×6″, *p* 90°, gbM	H59	59.2	23.8
MF, 7″, patch, lbM	.....	39 0.0	28.3
B, 30″×6″, *p* 80°, BNu., spindle	H60	12.7	32.8
F, 6″, patch	.....	13.6	11.4
B, 30″×6″, *p* 30°, gbM	H61	13.7	38.9
F, 5″, patch	.....	14.0	12.1
B, 8″×5″, *p* 135°	.....	19.6	19.3
B, 10″×6″, *p* 150°	H62	25.5	19.1
MB, 25″, patch, gbM	H63	31.6	41.2
B, 15″×10″, *p* 40°, patch	H64	33.5	34.8
F, 30″×4″, *p* 10°, sliver	.....	33.5	34.1
MB, 4″, almost stellar	.....	36.1	22.4
MB, 4″, almost stellar	.....	37.3	23.1
F, 5″	.....	40.8	28.7
MF, 3″	.....	41.5	19.7
F, 11″×6″, *p* 135°	.....	47.5	11.1
MF, 8″, patch, lbM	.....	51.6	24.5
MF, 8″×4″, *p* 40°, patch	.....	53.6	24.3
MB, 10″×4″, *p* 130°, spindle, bM	H66	55.0	16.1

I.C.I 1470, Cassiopeia

$\alpha = 23^h1^m51^s$, $\delta = +59°48'.9$ (1920); $\lambda = 78°$, $\beta = -1°$

Plate No. 297, 1917, July 21, 190m. S 23. Images intermediate and fairly round. Illustrated Plate XX*a*

A gaseous nebula lying in a rich region of the Milky Way. Its prominent feature is a bright thread of nebulosity irregularly triangular in shape, superimposed on the fainter nebulosity. The sides of the triangle are roughly 30″ long; the north side lies in *p* 88° and is straight, except for an abrupt bend to the N around a star directly in its middle; the *f* side in *p* 60° is shaped like an integral sign, while the *p* side, *p* 140°, is V-shaped, points inward, and has a faint star at its apex. The N and *p* sides do not quite join. The faint nebulosity is roughly 70″×45″ and is quite full of markings, which a longer exposure will show to advantage. A dark marking cuts across the nebula north of the triangle.

Three nebulous stars appear in the plate:

a,	314°	14′.8	Three stars involved in F nebulosity.
b,	197	10.7	Bright star in group of 5, involved in nebulosity.
c,	84	6.2	Two stars involved in nebulosity.

I.C.II 2233, Lynx

$\alpha = 8^h 8^m 19^s$, $\delta = +45°59'.5$ (1920); $\lambda = 141°$, $\beta = +35°$
Plate No. 2968 (Shapley), 1916, March 27, 30^m. S 27
Plate No. 359, 1919, December 23, 60^m. S 30. Images elliptical

The nebula falls near the edge of the plates of N.G.C. 2537 and appears to be a faint edge-on spiral $240'' \times 10''$, p 170° (no trail), with a faint stellar nucleus.

I.C.II 5146, Cygnus

$\alpha = 21^h 50^m 25^s$, $\delta = +46°53'.2$ (1920); $\lambda = 62°$, $\beta = -7°$
Plate No. 276, 1916, August 4, 60^m. S 23. Images small and round.
Plate No. 349, 1919, July 26, 300^m. S 23. Images small and elongated.
Illustrated Plate XIX*c*

This well-known nebula lies at the end of a dark lane which is well shown on Plate No. 349 and on the various published photographs of Barnard, Curtis, Franks, and Wolf. It surrounds the star B.D.+46° 3474 $9^M.5$, and its strong parts are $12'$ in diameter, while extensions run to the boundaries of the dark region in which it lies. Two of these extensions end at stars involved in nebulosity, *a*, p 257, d 9'.7, which is preceded by a bright patch, and *b*, p 156°, d 9'.8, where the nebulosity brightens on the preceding side of the star. The nebula is a wonderful array of dark and light markings and cannot be likened to any other object, although counterparts of certain configurations may be found in some of the other large gaseous nebulae. For example, the dark birdlike or torchlike dark markings in the Sp section, of which there are two, are similar to a marking in the p section of M 16; two dark indentations on the Np side resemble some of the indentations about the rim of M 8; and some of the canopied structure resembles the outlying parts of the Orion nebula.

MOUNT WILSON OBSERVATORY
April 1920

ERRATA in *Mount Wilson Contr.*, No. 132,
Astrophysical Journal, **46**, 24, 1917

Page 35: N.G.C. 2403, Plate V*c* was made from negative No. 307 (of the present series) instead of No. 169.
Page 41: N.G.C. 4594, the equation should read $V = -2.78x + 1180$.
Plate VIII*c*: N.G.C. 5544–5545, orientation of the plate is S at top, *f* at right; identification of nebulae in text is not correct; true description is found in the present series.
Page 42: N.G.C. 4900, $\alpha = 12^h 56^m 28^s$.

Reviews

Problems of Cosmogony and Stellar Dynamics. By J. H. JEANS. Cambridge: University Press, 1919. American Agents, G. P. Putnam's Sons, New York. Large royal 8vo. Pp. vii+293, figs. 44 and 5 plates. $6.50.

ABSTRACT

Equilibrium of a freely rotating single mass.—After giving the equilibrium equations for a rotating system and deriving a new and more exact *expression for the potential of any slightly distorted ellipsoidal figure*, Jeans discusses the stability of: (1) an incompressible fluid mass; (2) a compressible fluid mass; (3) an incompressible fluid nucleus surrounded by an atmosphere rotating with it; and (4) a gaseous mass in adiabatic equilibrium.

Equilibrium of a system of two masses.—The tides raised on a non-rotating sphere of incompressible fluid by an approaching rigid sphere are shown to be great enough to cause fission if the approach is sufficiently close. An atmosphere around the sphere would elongate toward the tide-raising body and might in case of near approach stream out in a pulsating manner. The problem of a *double star system consisting of two fluid masses revolving in a rigid configuration* is a very difficult one. Jeans's conclusion is that beyond stability a ring of broken fragments may be formed.

Origin of spiral nebulae.—Jeans's theory of their formation as a result of contraction accompanied by rotation which leads to equatorial breaking up is far from convincing. He relies on tidal forces which are admittedly infinitesimal and he neglects the possible effects of strong internal energy and of initial irregularities.

Origin of our galaxy.—Jeans's supposition that our galaxy is derived from a rotating nebula whose original radius of 30 parsecs increased to 2000 parsecs after the break-up, involves an age of only 500 million years and an expansion which the reviewer proves to be dynamically impossible. The reviewer points out that the excessively small chance of the close approach of two stars taken in conjunction with certain evidences of an approach to statistical equilibrium in our galaxy suggests an age which is beyond any order of time hitherto accepted.

Origin of binary and multiple stars.—Jeans's assumption that binary stars originate from nebulae by fission leads to deductions which can be reconciled with the facts only with the aid of arbitrary hypotheses. His picture of the cataclysmic birth of binaries is purely imaginary and very improbable.

Origin of the solar system.—As the Laplacian theory is clearly unsatisfactory, Jeans suggests a tidal theory, according to which the sun, originally a nebulous mass extending out to Neptune, was broken up by purely tidal action. The chief objection to this theory, aside from the improbability of the necessary encounters, is that it adopts the contraction hypothesis as to the origin of the sun's heat, a hypothesis

which is inconsistent with the conclusions of geologists and physicists as to the age of the earth and which is almost wholly unsupported by astronomical evidence.

Theory of cosmic origins.—While recognizing *Jeans's contributions* to the purely gravitational theory, the reviewer vigorously attacks the idea that stars and galaxies have their origin in the contraction of nebulae. The dynamics of our galaxy and the evidences of geology sharply deny the adequacy of this source of stellar energy. Unfortunately Jeans has accepted this contraction theory without question and is, therefore, led to make improbable assumptions necessary to reconcile certain points with that theory. His book is not, accordingly, a broad, open-minded discussion of the problems of cosmogony.

The English-speaking mathematical world is again under obligations to Professor Jeans for a careful and dispassionate exposition of a certain aspect of the physical world, his former works *Mathematical Theory of Electricity and Magnetism* and *Dynamical Theory of Gases* being already widely known. The labor of organizing into a coherent whole the many and diverse results which have been obtained in a given field, of adding to these results a sensible quantum, and finally of presenting a clear picture in an acceptable style is very great. The least that we, who have the benefit of all this labor for a small financial outlay, can do is to express our appreciation and grant such recognition as the work merits. From the point of view which he has adopted we believe that Jeans has succeeded in presenting as complete and strong a case as could be made; that point of view being a purely gravitational theory of cosmic evolution—a continuation, as Jeans puts it, of the work of Laplace, MacLaurin, Roche, Kelvin, Jacobi, Poincaré, and Darwin in the effort to interpret the cosmic forms through the agencies of the laws of motion and of gravitation alone.

The various forms in which interest centers are enumerated in chapter i. They are binary stars, spiral and other nebulae, and star clusters. Information with regard to these objects has been gleaned from many sources, and in concluding his review of these objects Jeans says: "The aim of a scientific cosmogony must be to trace these and other uniformities to their sources. When we find a formation repeated many times with only slight variations, we may feel confident that its origin is in every case the same. The problem of cosmogony is to discover these origins and to prove that they would lead to the observed formations."

Under the heading "Theories of Cosmogony" is given a brief review of the ideas of Laplace and Kant, together with certain modifications and criticisms of a later date. Under the subtitle "Tidal-Action Theory"

is included the planetesimal hypothesis. The description of this theory as given here is so different from that given by the authors, Chamberlin and Moulton, that we are compelled to believe that Jeans has not taken the trouble to inform himself as to what the theory really is, and when he concludes the description with the statement, "But whether all this can happen or not can only be decided by exhaustive mathematical investigations," we cannot avoid wondering what it is he is proposing to do.

The mathematical discussions begin with chapter ii, which opens with a statement of the conditions necessary and sufficient for a configuration of equilibrium in a system at rest. A clear and vivid exposition of Poincaré's notion of a series of such figures as a function of a parameter is given both descriptively and with the proper analysis. Diagrams illustrating the branch points, where one series of figures crosses another, help the reader very much in gaining an insight into the nature of the ideas and arguments involved, particularly into the difference in character of these branch points, which are always critical points in the stability of the series. The discussion of the conditions for equilibrium of systems in rotation yields the equations which the author wishes to use throughout the book for the figures of equilibrium of rotating fluid masses.

In the following chapter is presented an analysis for the figures of equilibrium of an incompressible fluid mass. Three classes of problems are recognized for which the analysis is fundamentally the same, but which differ vitally in their complications. The first problem is that of a freely rotating single mass. The analysis for the MacLaurin spheroids and Jacobi's ellipsoids is given, together with tables of numerical data and a discussion, following Poincaré, of stability along a certain series for which the density is constant. It is found that the MacLaurin spheroids are stable up to the point where they first meet the Jacobi ellipsoids, after which the stability passes to the ellipsoids. The ellipsoidal figures are stable up to the point where the pear-shaped figures begin.

The second problem is that of the tides raised on a spherical fluid mass by a distant heavy spherical body. When the tide-raising potential is limited to terms of the second order, two series of figures are found corresponding to the MacLaurin spheroids and the Jacobi ellipsoids. The ellipsoidal figures being physically impossible, there remains only a series of prolate spheroids which are stable up to $e=0.88$, for which the polar diameter is a little more than twice the equatorial.

In the double-star problem Jeans supposes two fluid masses revolving about one another in a rigid configuration; and of this problem there are two types: Roche's problem, in which one of the bodies is supposed spherical, and Darwin's problem, in which both bodies yield to the tidal forces. Here is given Roche's theorem that a small fluid satellite revolving about a very large spherical primary cannot be in equilibrium in any configuration whatever if its distance from the center of the primary is less than 2.455 times the radius of the primary. The results obtained by Darwin seem to prove that Roche's limit is altered by less than $2\frac{1}{2}$ per cent, whatever be the ratio in which the total mass is distributed between the two bodies.

The discussion of the stability mentioned above involves only such variations as are along an ellipsoidal series. A complete discussion requires a knowledge of the variations when the ellipsoidal figure is slightly distorted in any manner, and this requires a knowledge of the potential of any slightly distorted ellipsoidal figure. The author states that Poincaré's method of expansion in powers of a parameter with coefficients which are ellipsoidal harmonics cannot be readily carried out to the third power of this parameter, although the nature of the difficulty is not stated. As the second-order terms are not sufficient fully to determine the stability, the third-order terms must be obtained in order to effect a determination. Jeans has developed a method of his own for computing the third-order terms, and chapter iv is devoted to an exposition of this method and the attaining of the desired expression for the potential.

The solution of the question of stability is made possible by a sufficiently exact expression for the potential, and chapter v is devoted to an analysis for the stability. There is no difficulty in the tidal and double-star problems, for the spheroidal or ellipsoidal figures become unstable before the pear-shaped figure is reached, so that the pear-shaped figures for these cases are unstable. For the pear-shaped figures in the rotational problem, however, the matter is much more difficult, the ellipsoidal figures being stable right up to the point of bifurcation. Darwin's analysis in 1902 had indicated that these figures were stable, while Liapounoff's analysis in 1905 seemed to show that they were unstable. Thus the matter stood until 1915, when Jeans carried out the analysis which is outlined in chapters iv and v of the present volume. This computation shows that the pear-shaped figures are unstable at and near the point of bifurcation. Notwithstanding the fact that these figures of equilibrium are unstable, Jeans believes they are of great

importance in the subsequent dynamical motion, and that it is worth while, therefore, to trace the sequence of these figures of equilibrium. The labor of working out the three-dimensional figures is so great that he turned to the two-dimensional. He says:

> A problem which admits of very much easier solution is the two-dimensional problem of tracing out the sequence of configurations of a rotating cylinder of liquid. So far as the three-dimensional case has been solved, the analogy between the two-dimensional and the three-dimensional cases is so very close that we can reasonably hope that it will persist beyond. If this is so, we can discover the general nature of the solution of the three-dimensional problem by examining the much simpler two-dimensional problem. We accordingly turn to a discussion of the two-dimensional problem.

The analysis for the rotating cylinder is carried out in sufficient detail to be clear, and concludes with a series of figures, three of which are from computations showing how a very narrow constriction, or neck, is formed, and a fourth figure, which seems to be conjectural, showing separation into two quite unequal masses, and the paragraph:

> Thus we may with fair confidence assert that the two-dimensional series ends by fission into two detached masses, and in view of the close parallelism which we have discovered between the two-dimensional and the three-dimensional problems, it seems highly probable that the three-dimensional series will end by a similar fission into detached masses.

Since there are no stable figures of equilibrium in any of the problems considered beyond the spheroids and ellipsoids, the question naturally arises, What does happen? The answer is that the statical problem gives way to a dynamical one. Obviously when equilibrium is impossible motion occurs, and with considerable courage Jeans starts in pursuit of the tidal problem in chapter vi. The first approximation to the idealized tidal problem might be stated as follows: What would happen to a non-rotating spherical fluid mass, aside from mere translation, if a second large, rigid, spherical mass were made to approach within a certain distance of the first mass and then recede, the motion occurring along a straight line through the center of the first mass? The answer is that if the approach is sufficiently slow so that the primary can adjust itself to the figures of equilibrium, it will assume the shape of a prolate spheroid, continually lengthening until the final figure of equilibrium is reached in which the ratio of the major and minor axes is approximately 17:8; after this, the motion begins in a rapid lengthening of the axis of the prolate spheroid, which may or may not cease when the secondary begins to recede. In case the approach and recession of

the secondary is so rapid that the action may be regarded as impulsive, the primary oscillates along a series of prolate spheroids, provided the impulse is not too great. If the impulse is sufficiently great for the eccentricity of the prolate spheroid to pass 0.948, instability sets in, and a series of diagrams is given on which Jeans remarks: "Fig. 23 shews rough drawings (partly conjectural) of spheroids with the furrows produced on passing the earlier points of bifurcation. Little doubt will be felt that such figures will in time break up into a number of separate detached pieces."

The discussion is closed with a brief account of the effect of the forward motion of the secondary in an actual orbit. One effect is to set the primary into rotation, and another is to distort the primary into a boomerang shape. No account is taken of any original rotation of the primary, and no one will censure Jeans for this omission; the difficulties are far too great, but that it would effect a very serious modification in the results can scarcely be doubted. Perhaps a few paragraphs calling attention to this omission, particularly with respect to its effects upon the application of his results to cosmic processes, would have been in order. The direct and unmodified application of these results to a rotating mass would seem to be highly misleading.

The nature of the motion which occurs in the rotational problem beyond the series of Jacobi ellipsoids cannot be stated. One conjecture is that the incompressible fluid mass divides into two masses, the smaller being less than one-third of the larger mass, and that they continue to rotate as a rigid body as in the double-star problem. There are other possibilities, however.

The double-star problem, after stability ceases, is even more intractable than the rotational problem. The satellite is stable beyond a distance which corresponds closely to Roche's limit, but it cannot be followed mathematically for smaller distances. After a consideration of the various factors the author says: "Whichever way we approach the problem, the final result of the motion must be a ring of broken fragments, each fragment being so small that its forces of cohesion can resist the mechanical tendency to disintegration. Roche has suggested that Saturn's rings may have been formed in this way. . . . ."

The problem of compressible and non-homogeneous fluids is taken up in chapter vii. For matter of uniform composition Jeans shows that the figures of equilibrium can be specified by their boundaries alone, and that therefore the series of such figures must be a linear one, after the manner of the incompressible problem. Corresponding to the

MacLaurin spheroids there is a series of pseudo-spheroidal figures which become exactly spheroidal at the point where they branch into the Jacobi ellipsoids; then a series of pseudo-ellipsoidal figures which become exactly ellipsoidal again at the end of this series. The stability of these figures cannot be predicted from general principles for the rotational problem, but Jeans regards it as possible that the rotating mass may divide up into a number of detached masses instead of only two as in the incompressible case. The general case of incompressibility being too complicated and difficult, Roche's model is taken up. This model goes to the far extreme of compressibility in having a spherical rigid nucleus and an atmosphere of zero density. The simplicity of this model admits of the potential being written down at once, the upper boundary of the atmosphere being one of the equipotential surfaces. For a fixed volume of atmosphere and an increasing rate of rotation the upper boundary of the atmosphere finally develops a cusp or sharp edge at the equator, and for higher rates of rotation the atmosphere must escape at the edge, since the volume of the atmosphere decreases. A slight improvement upon Roche's model is made by assuming that the nucleus, instead of being a rigid sphere, is an incompressible fluid having the same rate of rotation as the atmosphere. This change does not alter the character of the results from the Roche model until the figure of the nucleus becomes ellipsoidal and the corresponding equipotential surfaces become pointed, so that the atmosphere escapes in two streams from these two points.

The same thing happens for the Roche model in the tidal problem. The equipotential surfaces become pointed first on the side toward the tide-rising body and then, if the tidal forces increase with sufficient rapidity, at both ends; and the atmosphere streams out from these ends in a pulsatory manner. In the double-star problem the two atmospheres merely unite, as would be expected.

The very wide gap between the incompressible model (A) on the one hand and Roche's model (B) and the modified Roche's model (C) on the other is filled for the rotational problem by the adiabatic model (D), which consists of a "mass of gas in adiabatic equilibrium, so that the pressure and density are connected at every point by the relation $p=\kappa\rho^{\gamma}$, where κ and γ retain the same values throughout the mass." The results of the analysis for this model are summarized by the author in the following paragraphs:

It follows that as we pass along either of the chains of models C and D which connect A and B, or along any other chain of models connecting A and

B, there must be some point on each at which fissional break-up gives place to rotational[1] break-up. At such a point the two methods of break-up must be about to begin simultaneously with the same rotation. Thus the condition determining such a point is that the centrifugal force shall be precisely equal to gravity on the equator of that configuration at which the rotation reaches such a value that a figure of revolution is no longer a stable form for the mass.

We have determined this critical point on each of the two chains of models C and D. Of these the adiabatic chain D is the more important. As we pass along this chain from A to B the value of γ varies from ∞ to 1.2; the critical point is approximately given by $\gamma = 2.2$. Thus a mass of gas or other compressible matter in adiabatic equilibrium will break up by fission if γ is greater than 2.2; it will break up equatorially if γ lies between 1.2 and 2.2. This latter range of course includes the values of γ for all gases whose density is so low that Boyle's law is approximately satisfied; for these γ is always less than 1.66.

Similarly as we pass along the C chain of generalized Roche's models, the value of s, the ratio of the volume of the nucleus to that of the atmosphere varies from ∞ to 0. The critical point is found to occur at about s equal to one third. Thus when the atmosphere is less than a third of the volume of the nucleus, the mass will break up by fission; when the atmosphere is greater than this the mass will break up equatorially.

Chapter viii is devoted to a discussion of the problem of von Helmholz, viz., the flow of energy associated with a contracting, and therefore radiating, mass of gas. Under the assumption that the laws of an ideal gas are obeyed, that the ratio of the specific heats and the opacity are constant throughout the mass and throughout the process of contraction, and that the mass contracts along a series of figures in thermal equilibrium, and certain other assumptions of more or less importance, it is shown that the temperature varies inversely as the radius of the sphere, a law which was first announced by Lane in 1870; and the conclusion is reached that the rate of radiation of energy is a constant, although Jeans does not wish to stand by this conclusion in its application to the sun. It is assumed that eventually the mass arrives at a stage where the density is so great that the laws of an ideal gas are not obeyed, and the rate of radiation falls. Finally, further contraction becomes impossible, and the mass merely cools off in accordance with Stefan's law.

As the application of the abstract theory of rotating masses to the cosmic forms proceeds, the argument becomes less mathematical and frankly more speculative. Thus in chapter ix a serious effort is made

[1] This word should evidently be "equatorial" instead of "rotational," as in the preceding paragraph it is stated that the method of break-up which occurs in Roche's model will be referred to as "equatorial" break-up.

to show that the spiral nebulae have developed out of vastly extended masses of gas. Since the observed spiral nebulae are obviously dissimilar in their details, a purely mathematical theory of them is impossible; their striking similarities, however, suggest a common process which must have a mathematical theory. The argument threads its way through a very complicated and difficult field. It contains many points that are speculative and highly debatable; but it is better to limit ourselves here to the picture which Jeans describes.

Since, as he says, every permanent astronomical body must contract, our extended nebula, once in existence, will do so also. The heavier elements will find their way to the center; and when a rotating figure of equilibrium has been attained the equilibrium will be intermediate between an isothermal equilibrium, for which γ, the ratio of the specific heats, is unity, and an adiabatic equilibrium, for which γ might be equal to $5/3$. Inside of this range of values for γ the mass in its process of contraction must arrive eventually at the point of equatorial break-up. The maximum value of γ for which equatorial break-up is possible is $\gamma=2.2$. Diagrams showing a meridianal cross-section for $\gamma=1.2$ and $\gamma=2.2$, just as the process of break-up is about to begin, are given and are compared with photographs of nebulae seen edgewise. In two of these photographs fair resemblance to the case $\gamma=2.2$ is clear, but a rather meager resemblance for the case $\gamma=1.2$. The photographs suggest diamond rather than lenticular shapes. Balancing the probabilities as to the values of γ, the author arrives at the equation $\omega^2=0.035\times 2\pi s$ for the relation between the angular velocity and the mean density at the time when the cuspidal edge is formed. The photographs evidently represent a stage beyond this critical stage. Furthermore they cannot be supposed to represent rigid bodies as do the diagrams. The author himself departs from the equilibrium theory in assuming that the outer parts of the nebula are rotating faster than the inner, and the effect of this departure is to modify the diagram in the general direction of the photographs.

Just what happens after the critical stage sets in is the interesting thing, and unfortunately no one can say. Jeans extends a theorem of Laplace and proves that if a ring is formed it must have a density greater than $1/3$ of the mean density of the nucleus. This disposes finally of the Laplacian idea as to the formation of the planets in the solar system, if there is anyone who still has any lingering doubts about it.

If a ring cannot form, what can happen? Here Jeans appeals to the tidal forces of the rest of creation, which are admitted to be

infinitesimally small, and assumes that these forces would tend to fix two points on the equator at which and only at which matter would stream forth. Once a stream of matter has begun to issue forth, the tidal forces will be reinforced by the matter already ejected, so that the stream presumably will increase. The matter will not issue forth uniformly; rather it will come in waves, and the interval between the waves is defined by the very simple relation $c=l\omega$, where c is the molecular velocity, and ω is the angular rate of rotation. In order that this filament may not simply scatter into space, its line density must be comparable with $2/3(c^2/k^2)$, where k^2 is the constant of gravitation. Given the line densities and the length of the waves, it is possible to compute the mass of each of the waves. Using what seem to be probable values, their mass turns out to be eight times the mass of the sun, so that the nuclei in the arms of the spiral nebulae are comparable with the mass of the sun.

It is difficult to believe that the tidal forces mentioned above would act in the way which Jeans describes. Inasmuch as they were in existence before the critical stage set in it seems more probable that they would set up infinitesimal waves of distortion in the rotating mass, for the direction of the tidal forces would be a fixed direction. These waves of distortion might be effective in determining the course of evolution after the critical stage set in, but they could hardly have the effect of pulling out streams of matter from the rotating mass. The molecules at the sharp edge are, in effect, satellites revolving in circular orbits about the primary mass. The effect of the tidal forces would be merely to slightly perturb their orbits. Presumably these perturbative forces would be very much smaller than the perturbative action of the sun on the moon, and yet the moon shows no tendency to rush straight out toward or away from the sun. Such effects as Jeans describes might perhaps occur if a non-rotating mass were held in equilibrium in one of the lenticular figures by suitable fictitious forces. But once a molecule is freed from a rotating primary it takes to orbital motion, and the tidal forces would be merely perturbative. It must be borne in mind that Jeans does not invoke the highly active internal forces which are a vital element of the planetesimal hypothesis of Chamberlin and Moulton, to which Jeans's hypothesis bears a strong superficial resemblance. His primary mass is a quiescent one, and the forces of ejection are tidal. The omission of a strong internal energy seems to be a fatal one.

Chapter x is devoted to a statistical study of stellar systems with particular application to our own galaxy and to globular star clusters.

Our own galaxy[1] is supposed to have been derived from such a rotating nebula as is described in chapter ix. At the stage of break-up of the nebula the equatorial radius was about thirty parsecs, and the period of rotation was of the order of 160,000 years. After the break-up into the units which are now the stars, a process of expansion is assumed to have set in which enlarged the system to its present dimensions of 2000 parsecs radius, and presumably the galaxy is still in the process of expansion. Obviously such an expansion must have occurred if the hypothesis as to its origin is admitted, for the present dimensions are some sixty-six times the supposed original one. The fact that such an expansion is dynamically impossible, however, merely shows that the hypothesis as to its origin is inadmissible.

The proof of this impossibility is very simple. At the moment when instability of the rotating mass set in the relation $2T_0+W_0=0$ existed, where T_0 is the kinetic energy and W_0 the potential energy; thus $T_0=-\frac{1}{2}W_0$, and the total energy T_0+W_0 was equal to $+\frac{1}{2}W_0$. Suppose now that the process of radiation ceased altogether, and that all of the kinetic energy was absorbed in the process of expansion. Under these assumptions, which are the most favorable possible for a maximum expansion, the total energy, $E=T+W$, would be constant, and equal to $\frac{1}{2}W_0$. Let the subscript 1 indicate the value at the end of a process of uniform expansion. Then $\frac{1}{2}W_0=T_1+W_1$. But if T_1 is zero, then $W_1=\frac{1}{2}W_0$. Since the configuration has remained unaltered the relation $W_1=\frac{1}{2}W_0$ says that the size of the configuration has merely doubled, and that every molecule is at rest. If the configuration has altered, which is actually assumed in Jeans's hypothesis, it must still be true that $W=\frac{1}{2}W_0$, and any increase in the radius beyond two must be offset by a corresponding increase in the density near the center. In other words, only such configurations are admissible as will change W into W_1 without any work. Now our galaxy at the present time is by no means without kinetic energy, and there is no evidence whatever of a strong central condensation such as would result if the outer boundary had expanded many diameters. We can only conclude, therefore, that an expansion to 66 diameters is wholly impossible.

If we assume that a system of stars moves in such a way that $W=-k^2/\sqrt{I}$, where k^2 is a constant factor of proportionality, and I is the moment of inertia with respect to the center of mass, and such would be the case for any configuration which merely altered its linear

[1] Throughout the volume Jeans has used the word "universe" as synonymous with the word "galaxy"; obviously, the galaxy is but a part of the universe.

dimensions, then Eddington's equation $d^2I/dt^2=4T+2W$ can be written $d^2I/dt^2=4E+2k^2/\sqrt{I}$. For any permanent system the energy, $E=T+W$, is a negative constant, and the integration of the foregoing equation shows that I oscillates with a period equal to $2\pi k^2/(-2E)^{3/2}$. So far as these assumptions are applicable to spiral nebulae, and the assumptions seem fairly reasonable ones if the spiral form is anything like a permanent one, then, unless the size is a constant one, it can merely oscillate—sometimes expanding, sometimes contracting. On the assumptions that our galaxy is an oblate spheroid the axes of which are in the ratio of 10 to 3 and the equatorial radius 2000 parsecs, that there are 1.5×10^9 stars uniformly distributed and of such mass that the mean density of the spheroid is 5×10^{-23}, and that the average star has a velocity of 25 kilometers per second, and these are the figures actually adopted by Jeans, then if the galaxy is expanding at the present time its period of oscillation is 25 million years, and at the end of this period it must have returned to the condition from which it started. This period would be increased to 100 million years if the density were only 1/5 of that previously assumed and the velocities were increased from 25 to 40 kilometers per second. According to Jeans's hypothesis the process of expansion has been going on for something like 500 million years and is still continuing. The entire period of oscillation, therefore, must be well over 1000 million years, and such a period is inconsistent with our present astronomical data.

The frequency of close approach of stars is the next topic discussed, and the effects which these individual encounters have in diverting the path of a star from a straight line; in other words, in developing a cross-velocity. Inasmuch as this cross-velocity amounts to only 1 kilometer per second after 40,000 million years in our own system, it is clear that the effects of individual encounters in a period of 500 million years, which Jeans regards as the order of astronomical time, would be negligible; and the motion of a star depends almost entirely on the massed action of all the stars of the entire system. As Jeans puts it, "the problem of stellar dynamics is the same as the problem of the kinetic theory of gases with the collisions left out," and is therefore very much simpler.

The study of the distribution of the stars, particularly with respect to steady states of motion, shows that, except for certain artificial cases, "the only possible configuration for a cluster of stars moving freely under their own gravitation in steady motion are those in which the stars either form a spherically symmetric figure or a figure of revolution which is symmetrical with respect to an axis." With respect to

our own system of stars the indications are that we are approaching a steady state but have not yet reached it. After an examination of the rate of approach the author states: "Thus it appears that after an interval of 10,000,000 years the courses of the stars will be little altered; their orbits over 10,000,000 years are not far removed from the straight lines they would describe if gravitation were suddenly annihilated. It is clear that the approach to a steady state is an excessively slow process." In order to reconcile this perfectly obvious conclusion with the apparently obvious conclusion that our system of stars has already approached a steady state of motion in the not-at-all obvious period of 500 million years, recourse is had to the previous notion that in the early stages of the process the radius of the galaxy was only 30 parsecs, and consequently the stellar density was about 300,000 times as great as at present. In this condensed condition the time requirements would be very much less severe, and "what gravitation fails to accomplish now in 10 million years may have been accomplished in 10,000 years when the system was young and the stars closely packed together." As the assumption that the system has expanded in the previously described manner cannot be granted, the reconciliation has not been effected, and we are forced to the conclusion that the period of 500 million years is very seriously in error.

Other interesting conclusions of this statistical study are that the phenomenon of star-streaming does not exist when the steady state of motion has been attained; that a steady state of motion can never be perfectly attained by a stellar system; and that in our system the stars of types A, F, G, K, and M seem to be approximately in a steady state, while the B-type stars do not.

Chapter xi is devoted to a consideration of the origin and evolution of binary and multiple stars. It is taken for granted, without question or argument, that binary stars have originated from a single nebula by a process of fission, although in the last paragraph of the chapter the possibility is recognized that a binary star may have originated in some exceptional cases from what might be called a double nebula. The preliminary considerations in which the gas is thought of as an adiabatic mass of air leads to the following conclusions:

a) No binary star which has formed by fission can have a density of less than about $\frac{1}{4}$.

b) No giant binary can have been formed by fission.

c) The temperature of a binary star which has been formed by fission must decrease as its evolution progresses.

These conclusions being out of harmony with observations Jeans finds it necessary to revise his data. The justification of this revision is sought in the high internal temperatures of the stars, which, according to Emden and Eddington, may be as high as 10,000,000 degrees. This high temperature may modify the properties of the gas so that fission becomes possible. In short, Jeans assumes that, since the star is double, fission must have occurred. Jeans's process of fission is different from that of Darwin in that Darwin thought of it as a statical process, while Jeans thinks of it as cataclysmic, i.e., the two components were separated with considerable relative velocity. Owing to their elliptic motion, however, they must continually collide at periastron with a diminution of eccentricity at each collision. These repeated collisions keep getting milder and milder until finally the two stars just graze one another at periastron, the eccentricity being reduced not quite to zero, and the process of fission is complete.

The foregoing process is largely an imaginary one, as it is far too complicated to follow with an exact analysis. If the two stars were just in contact one would infer from the analysis of chapter vii that the figure of the smaller mass was unstable, for it would have been unstable for both the incompressible model and the modified Roche model. To assign an eccentricity to the relative orbit of the smaller body would seem to make matters worse, for, even if the figure was stable but very close to instability, a collision due to the eccentricity would probably precipitate another cataclysm and result in the scattering of the material of the smaller body in the form of a ring. It does not seem possible to get the smaller mass outside of the Roche limit in safety, and it is very hard to see how a double star can result from the process of fission. If this difficulty is in reality an insuperable one, it would seem that Moulton was correct in his opinion that Darwin overestimated the importance of these forms of equilibrium from an astronomical point of view.

Laying aside this difficulty, however, we proceed to the effects of tidal action on the subsequent evolution, and it is to Darwin that we owe the foundations of this study. One of the first conclusions reached is that the tidal action increases both the eccentricity and the mean distance. But it is very quickly found that for homogeneous masses the latus rectum cannot be doubled, however long the tidal action may have continued. The range is still less for compressible masses, provided the ratio of the masses does not exceed $2\frac{1}{2}$ to 1. As for the period, it is found that the maximum increase is 13.6 times; for most binaries however the maximum is 4.4 times. Furthermore Jeans concludes:

Thus under no circumstances can the semi-latus rectum of a binary system in which $M/M' < 2\frac{1}{2}$ exceed the mean radius of the primitive nebula at the instant at which the spheroidal form became unstable. . . . . If we suppose the spectroscopic binaries to have originated by fission the problem of explaining why it is that short period binaries are generally of small eccentricity of orbit and of early spectral type, the reverse being true of long period binaries, admits of no answer so long as we regard a binary star as a self contained dynamical system.

In 1909 the Carnegie Institution of Washington published a volume, entitled *The Tidal and Other Problems*, which contained two papers by F. R. Moulton on the formation of binary stars by the process of fission and their subsequent separation by tidal action as imagined by Darwin. The results of these papers were again summarized by Moulton in his *Introduction to Astronomy* (second edition, 1916, p. 543). Neither of these publications is referred to by Jeans, although they contain most of the conclusions which he has reached in his discussion and many others. On the whole, these conclusions, first arrived at by Moulton and later by Jeans, are against the hypothesis that binary stars originated from a single star by a process of fission due to rapid rotation, without, however, completely disproving it. It appears from both discussions that if the fission occurred at all it must have occurred while the star was still in a very tenuous nebulous state; and to the reviewer it seems that the formation of two stars from a single nebula was due, if it occurred at all, to irregularities in the density of the nebula rather than to the process of fission as described by Darwin.

In order to give the fission theory the benefit of every possible doubt, however, Jeans next takes into account the influence of the other stars on the supposedly new-born binary star. The general effect of the mass of all the stars upon the system is merely tidal, resulting in minute perturbations. The secular effect is infinitesimal, so that there remains only the effect of the individual encounters. Any single encounter might result in any kind of an effect, owing to the great variety of circumstances and conditions under which the encounter might take place. The statistical effect of very large numbers of encounters, as implied by the equipartition of energy, is to make the eccentricity tend toward the definite value $e=0.637$ and to increase the major axis. "Any group of stars which has experienced a large number of stellar encounters will have orbits in which the eccentricities are ranged according to the law $2e\,de$ round a mean value of $2/3$, while the periods will depend on

the mass of the star, being of the order of a year for stars of the average mass 1.7 times the mass of the sun."

Thus the effect of stellar encounters with the binary system is to bring the fission hypothesis and the subsequent evolution into harmony with Campbell's table, which exhibits the relations between the various types of stars and their periods and eccentricities. A very interesting point which is not discussed is the survival of a binary system as a result of the first few encounters when the binary is still struggling to maintain its dual character. What proportion of them would survive, and what proportion of them would experience another cataclysm? Apparently 35 to 40 per cent of the stars are binary. The only star which we can observe directly has a very low rate of rotation, suggesting naturally that many other stars are in a similar state of poverty as to rotation. Bearing this fact in mind, and the further fact that a binary once formed was subject to many vicissitudes in its struggle to maintain duality if it was formed by the process of fission, it must be admitted that the number of stars that actually are binary is surprisingly large.

There remains one more difficulty in Jeans's appeal to the equipartition of energy, viz., the interval of time necessary for many encounters. An encounter as close as Neptune is to the sun would occur once on an average in an interval of time which is of the order of a million million years, and to have any statistical effect very many such intervals must have elapsed. The effect of a single encounter at this distance upon a close and rapidly revolving binary would be very small, as is clear from the fact that the presence of the sun lengthens the moon's period by about one hour only, and even this effect would be greatly reduced if the moon were almost in contact with the earth, as would be the case in a binary newly formed by fission. The average time interval for an encounter as close as the sun is to the earth is of the order a million billion (10^{15}) years. It is clear, therefore, that if the dynamics of our galaxy are such as would be expected from the use of statistical methods, and it is becoming more apparent year by year that this is approximately true, then the age of the galaxy must be great beyond any order of time which has hitherto been commonly entertained. Jeans's hypothesis that the process was relatively much more rapid a few hundred million years ago because the system was at that time very much condensed cannot be admitted, since the energy of the system is definitely against it. We are face to face with a new conception of the order of astronomical time.

Just as a single star divides by the process of fission into a binary, so a binary at a later stage may subdivide into a triple or multiple system. If it does so the density at the second division must have been greater than 342 times the density at the first division, and the periods will be of the order of 18 to 1. An interesting summary of a statistical study of triple systems by Russell is given. From this study it is concluded that systems in which the separation of the components is less than 1000 years' proper motion may have formed by fission, while systems in which the separation is greater than 1000 years' proper motion may have had a different origin, possibly from a double nebula.

The last chapter of the book, chapter xii, deals with the origin and evolution of the solar system. Naturally the rotational picture as described by Laplace receives the first consideration. The weight of modern opinion is rather decidedly adverse to the Laplacian system of rings, and, with perhaps a mild reservation, Jeans agrees with this decision. In addition to other difficulties, many of which are carefully analyzed, this hypothesis implies that the sun should have divided into a binary, which it has failed to do.

The only other hypothesis considered is what Jeans calls the tidal hypothesis, which bears a very close resemblance to the planetesimal hypothesis, though not identical with it. The tidal hypothesis considers the break-up of a gaseous mass by purely tidal action, and for this purpose a vastly distended condition of the sun, even out to the orbit of Neptune, is considered most favorable. The planetesimal hypothesis, on the other hand, presupposes a sun much the same as our present sun, with a very high order of internal energy, the tidal action serving merely to release and direct the action of this internal energy. In the early stages the two ideas are quite different, although in the later stages the two types of evolution are much the same.

The general harmony of our actual system with this idea is first noted, and then the details are brought before the bar for examination. Obviously the first objection is the improbability of a close encounter happening. In the present state of the galaxy an approach to within three times the distance of Neptune would occur only once on an average in 300,000 million years, although in the earlier hypothetically condensed condition of the galaxy this interval would be reduced to 3 million years. For an expanded state of the sun Jeans might have made this objection much stronger, for if his former conclusion that the rate of radiation is constant is correct, and if the present rate of radiation is the

same as the earlier rate, then the sun would have shrunk from an infinitely distended state in periods given in the following table:

Distance	Years	Distance	Years
Neptune	2940	Mars	58,000
Uranus	4600	Earth	88,000
Saturn	9250	Venus	122,000
Jupiter	16,000	Mercury	228,000

Present size, 18,900,000

Thus the improbability of the event depends, even for the condensed condition of the galaxy, upon the size of the sun which is adopted. Under the most favorable assumptions there would be only one chance in a thousand for the conditions which Jeans considers most favorable for tidal action. In this respect a sun of the present size, as postulated by the planetesimal hypothesis, has a great advantage; but for a purely tidal theory this condensed condition of the sun would require a much closer approach of the secondary sun and consequently a very much more extended time interval, the time interval varying inversely as the square of the distance of closest approach.

We shall not follow Jeans through the detailed examination of this hypothesis, which is more or less familiar to those who are interested in this subject. It will be sufficient to quote his final paragraph:

> This vague sketch of the tidal theory will, it is hoped, be read as an indication of the possibilities open to the tidal theory, rather than as an attempt to advocate the theory or present it in a final form. The theory is beset with difficulties, and in some respects appears to be definitely unsatisfactory. To the author it appears more acceptable than the rotational theory, or any other theory so far offered of the genesis of the solar system; but an enormous amount of mathematical research appears to be needed before the theory can either be advocated with confidence or finally abandoned.

To the reviewer the planetesimal hypothesis, as set forth by Chamberlin and Moulton, seems much preferable to the purely tidal theory as discussed by Jeans, for the questions of density of the detached masses are far less troublesome. Furthermore the planetesimal hypothesis will survive even though the idea that the sun has condensed from a vastly distended nebula be discarded; while the purely tidal hypothesis apparently will not.

The last topic discussed by Jeans is the time scale. The gravitational theory of the sun's heat provides for 20 million years, and

the radioactive sources do not add much to this. The estimates of the geologists as to the age of the earth seem to converge to a period of some 250 million years. As for the galaxy, only ten oscillations of a star across the galaxy require 3000 million years, and hardly less than that would suffice for the present distributions of the stars and their velocities. These estimates are discordant, but the time for the galaxy can be reduced by supposing that it was once in a much-condensed condition, so that the time of an oscillation was much smaller. He states that the age of the sun can be much lengthened by supposing that three-fourths of the sun's energy has been radiated in the last 15 million years, while the remaining one-fourth was dissipated during an interval of 200 million years, notwithstanding that this last supposition violates the former conclusion that the rate of dissipation should be a constant. Balancing up these various estimates he concludes that the age of the galaxy is of the order of 500 million years, and that there are no difficulties of a serious nature on the score of time.

The volume is brought to a close with a brief résumé of the ideas which have just been discussed, and a statement that these ideas merely seem more probable than others in the present state of our knowledge. No final decision is as yet possible.

Human nature is cautious and conservative when considered in the mass. An idea, once well established, continues to survive generation after generation, even long after its usefulness has ceased. A sort of intellectual inertia preserves its existence, much in the same fashion as a religious dogma. During the early part of the nineteenth century the Laplacian nebular hypothesis made a wonderful appeal to the scientific imagination of that era. Its beauty and simplicity and apparent harmony with the observed facts established it in a position of security and confidence, so that it modified very profoundly the scientific thought of the entire century. By the middle of the century ideas had become much cleared with respect to the doctrine of energy, and in particular the mechanical equivalence of heat had been established. This enabled von Helmholz to make a great contribution to the nebular hypothesis, and indeed the only essentially new idea that has ever been added to it, by showing how the heat of the sun could be supposed to have been maintained by the process of contraction; and that this source would be sufficient to provide the sun with energy at its present rate of emission for about 20 million years.

By this time the doctrine of evolution in its entire generality had been established by Herbert Spencer, and a highly developed special doctrine in the field of biology by Charles Darwin. The geologists were accepting the doctrine of uniformity in the geological processes instead of their previous notions of geological catastrophes. Gradually the geologists and biologists began to find themselves cramped by the limitations on time which the astronomers and physicists were imposing upon them. Unable to come to any agreement with the astronomers and physicists on the questions of time, the geologists and biologists went their own way and ignored the astronomers and physicists altogether. The evidences close at hand in their own fields were far more certain, more tangible, and more numerous than the mere speculations of the astronomers as to the sources of the sun's heat. The implications of these evidences could not be ignored. Gradually the geologists extended their time estimates from a few millions of years to a few hundreds of millions. Increasing geological evidence has uniformly pushed upward their time estimates, until now there are reliable estimates as high as 1600 millions of years.[1] That these estimates are out of harmony with the Laplacian doctrine is nothing to them; let the astronomers look after their own troubles. In this attitude the geologists are strictly correct, for they are following their own lines of evidence.

The discovery of the radioactive processes some twenty years ago seemed for a time to offer the astronomers a way out of their embarrassment, but at best the relief was but a partial one, and their time estimates are far below the demands of the geologists. But worse was still to come, from the Laplacian point of view. Not only have the geologists attacked the Laplacian implication as to time, but they have also attacked the Laplacian implication as to a once molten earth. Professor T. C. Chamberlin finds the evidences of earth structure out of harmony with a once molten condition, and in collaboration with

[1] In a very careful study of the various lines of evidence as to the age of the earth Arthur Holmes (*The Age of the Earth*, 1913) showed that there are only two that have stood the tests of destructive criticism; one is the geological and the other the radioactive. The geological methods rest upon measurements of the amount of salt in the oceans, the thickness of the sedimentary strata, and the deposits of calcium carbonate. These three lines are not independent but are intimately related. The estimates from them are concordant, 100 million to 300 million years, but they stand or fall together. The radioactive method, which commands a higher confidence on the part of the geologists, leads to estimates as high as 1600 million years for the age of some of the oldest rocks, and evidently the earth itself is still older. The reconciliation between the two methods is effected by showing that the geological methods lead to minimum estimates only.

Professor F. R. Moulton has offered a hypothesis as to the origin of the planetary system which is more acceptable than the Laplacian hypothesis, not only to many geologists but also to many astronomers. The formulation of the planetesimal hypothesis by Chamberlin and Moulton has necessarily involved renewed attacks upon the Laplacian hypothesis, so that even Jeans casts his vote against it so far as the formation of the planetary system is concerned.

These attacks upon the origin of the planetary system have not, however, directly involved the question of the origin of the sun. Except that they insist upon having their allotted interval of time, the geologists are quite willing that the astronomers should let their suns condense out of nebulae if they wish to; but the geologists must have plenty of time. This is precisely the condition which the condensation hypothesis will not permit. On the hypothesis that the energy of the sun is due to its contraction, and that the rate of radiation is constant, the age of the sun cannot exceed 20 million years. To suppose, as Jeans has done, that this period can be extended to 250 million years by imagining that the rate has been constant during the last 15 million years, and only one-fortieth as great as at present during the remainder of the time, is merely playing with words, for the actual effect would be to reduce the geological period to 15 million years, and not to extend it to 250 million years, because if the earth received only one-fortieth of its present quota of energy it would be a solidly frozen waste. Any other hypothesis as to a reduced rate of radiation in the past encounters the same trouble—it reduces the geologic period instead of extending it. The conclusion is therefore unavoidable on geologic grounds that the energy of the sun does not come essentially from the process of contraction, and that the entire Laplacian conception of the origin of stars from contracting nebulae is incorrect.

It is not necessary for the astronomers to go to the geologists for this conclusion. The structure of the stellar systems has implications as to time as certainly as has the structure of the earth. On the general principle that the whole is greater than a part one would naturally expect the order of astronomic time to be vastly greater than the order of geologic time. This anticipation is amply justified by the dynamics of the galaxy. The close approach of two stars is an event of fundamental importance in the system; and if one astronomical unit be the order of approach the expectation of any one star is of the order of a million billion (10^{15}) years. At the distance of Neptune it is of the order of a million million years. Jeans has shown in the present volume

that a cross-velocity of one kilometer per second would be generated by the more distant encounters in a period of something like 40,000 million years. He is furthermore in agreement with Charlier that the cross-velocity would be of the same order of magnitude as the velocity itself in a period which is of the order 10^{15} years. He states also that the galaxy is well along toward a state of steady motion, and that in the present state of the galaxy the rate at which this steady state is being approached is an excessively slow one. In these statements we are in hearty accord, and we are perfectly willing to accept their logical implication that the age of the galaxy is excessively great.

This conclusion is in harmony with what we see at present. It is not in harmony with the contraction hypothesis as to the origin of the stellar energies. Indeed, there is but little that is in harmony with this hypothesis save the law of gravitation itself, and there is nothing in this single harmony to compel us to believe that it is an essential factor in the case. Observational astronomy does not support it. There are no examples to which one can point with any certainty by way of illustration. There is no sequence of figures showing the various stages of a process that is supposed to be universal. There are many nebulae in the sky, but they show no tendency toward spherical shapes, and even the planetary nebulae fail to stimulate our hopes. The galaxy should be full of masses of stellar dimensions which are dead and cold and solid, but there is no evidence of any such. The earth is the largest body, of which we have any certain knowledge, that is solid. Jupiter and Saturn are almost certainly purely gaseous, while Uranus and Neptune seem to be neither purely solid nor purely gaseous. The range of masses of the stars, so far as we know them, is not great, while under the condensation hypothesis we have no reason to anticipate any limits at all. The relatively large number of runaway stars forbids us to believe that they are merely ejected members of our own system, and if they have come from other galaxies we are forced to believe that they, at least, are very old. The almost incredibly large number of temporary stars tells us unmistakably that the cosmos knows of other things than the law of gravitation and the kinetic theory of gases. In fact, in whatever direction we may push our inquiries, we find little or nothing to encourage our faith in the hypothesis of contraction.

The spectral types of the stars fitted in with it fairly well, but it is a case of fitting in with it rather than a case of lending it any support. In the way of genuine support of an observational character there is virtually nothing. It has had a highly respected past because the

simplicity of the idea has attracted to it the talents of great mathematicians. The name of Laplace gave it standing from the beginning. Von Helmholz rescued it from an early grave by showing that the contraction would produce vast amounts of heat; while Lane showed that the production of heat was greater than the radiation, and that therefore the temperature would rise. Darwin suggested that an excess of angular momentum might cause a mass to divide into two masses. Not only would this process of fission explain the origin of our own moon, but it could also be called into service to explain the existence of binary and multiple stars. This idea seems to have fascinated Poincaré, and it was the inspiration of his great paper on the figures of equilibrium of rotating fluid masses.

This very brief review of its history shows that the mathematicians have had a grand time with the hypothesis that the stars have had their origin in the contraction of a nebular mass. It challenged their powers without ever wholly discouraging their efforts. The early successes of Laplace, Helmholz, and Lane and the partial success of Darwin have given the hypothesis an almost universal currency, so that Jeans accepts it as a fundamental postulate without even a question. To him "the problem of cosmogony is to discover these origins [of astronomical forms] and to prove [by means of the contraction hypothesis?] that they would lead to the observed formations." If this be accepted as a definition of the scope of cosmogony, then cosmogony is merely a subtitle in the more general subject of cosmology, which might be defined as the study of the transformations of energy throughout the cosmos, the study of origins being of no more interest than the study of dissolutions; the study of forms, however, is vital, as they are our only observational means of determining the transformations of energy which are occurring.

Looked at from this point of view the contraction hypothesis is seen to be a very one-sided affair. It postulates the existence of the necessary nebulae with no inquiry as to the origin of the nebula, a matter which is just as important as the star itself. It is satisfied to bring the picture down to date and to ignore altogether the question of dissolution. There are some hundreds of thousands of spiral nebulae which, as many believe, may be galaxies like our own. They are in varying states of development; but if the radiation of their stars is limited to some such period as 1000 million years, which is a very generous estimate for the contraction hypothesis, we cannot help but wonder how so many of them got started all at once, for 1000 million years is a very brief time, so far as we can see, in the total physical existence of a galaxy. In a

few hundreds of millions of years they will all be cold and dead and literally petrified. But they still exist, even though the light of the skies be all gone. For millions of billions of years they plow their way through darkness. Even a collision of two galaxies would not result in a catastrophe, though it might result in a slight scattering of the dead stars. The period of light and luminescence is as but a flash of lightning as compared with the period of darkness and death, a period which would seem to be so long that we are almost tempted to call it permanent.

It would scarcely seem possible that anyone could entertain so dismal a picture, and yet it is a logical implication of the contraction hypothesis.

So much for the future of the astronomical forms which we see! What becomes of the radiant energy which the stars are pouring into space at such an extravagant rate? Are we to suppose that it too pursues an endless journey with no further incidents than an occasional reduction in wave-length as a consequence of its interception by some physical mass? As the contraction hypothesis says nothing whatever on this subject we are at liberty to believe what we please, for we are in the fields of cosmology, and not cosmogony.

More strictly, to the domain of cosmogony belongs the question as to the origin of molecules, atoms, and electrons. In the days of Laplace and von Helmholz the atom was a fundamental and permanent physical unit; there was no need of considering its origin. Today we recognize that it has an organized structure—a unit that has been built up, as have all the other units, and likewise susceptible to destruction. Their vast numbers are comparable, so to speak, only with the vastness of astronomical space; for if the mass of the solar system were uniformly distributed over the sun's share of space there would be approximately 10 cubic centimeters of space for each atom, and relatively to their sizes they would be as far apart as are the stars. The energy required for their organization also is very great, so that one can scarcely avoid the conclusion that their origin is an astronomical affair. If this speculation is correct, then the problems of cosmogony are very largely extended. Not only must the stars and galaxies be accounted for, but also the electrons, atoms, molecules, and nebulae. Fortunately our information with respect to the physical units, from electrons to galaxies, is very rapidly advancing. In the domain of cosmology facts are outstripping theory. We are very greatly in need of intelligent speculations, particularly speculations which will co-ordinate the physical processes of the cosmos and make intelligible the ebb and flow of energy as it surges

up and down the series of physical units. It was this service that the contraction hypothesis rendered to the scientific thought of the first half of the last century. But it is not sufficiently comprehensive in its scope nor sufficiently in agreement with our interpretations of observations to be any longer acceptable.

Jeans has made a splendid exposition of the theory in the present volume, and we are grateful to him for illuminating many points which have not hitherto been clear. But the real value of his analysis has been obscured by two unfortunate errors: the first of these was the attempt to harmonize the age of the galaxy with the age of the sun, by supposing that the galaxy was formerly in a very much condensed condition so that the process of the distribution of the velocities of the stars proceeded much more rapidly than at present; the second was the attempt to harmonize the age of the sun with the geological estimates of the age of the earth by a mere play upon words. It would have been much better had he regarded the contraction theory as a hypothesis to be tested rather than as a postulate into which other things must necessarily fit. Had he done so, he would not have left with the reader the impression that the process of fission satisfactorily accounts for the binary stars, and that the gravitational source of the sun's heat is quite adequate for all purposes. The facts, as we see them, are quite the contrary, and a frank recognition of these difficulties would have compelled an equally frank rejection of the condensation hypothesis, thereby clearing the way for newer pictures which will not only take into account the discoveries of modern physics with respect to the structure and elemental properties of matter but will also harmonize with the equally wonderful advances of the astronomers in their studies of the structure of the cosmos.

W. D. MacMillan

University of Chicago
April 1920

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